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Using Motion Perception to Improve the Nighttime Conspicuity of Bicyclists at Street Crossings

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USING MOTION PERCEPTION TO IMPROVE THE NIGHTTIME CONSPICUITY OF BICYCLISTS AT STREET CROSSINGS

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ABSTRACT

Recent literature indicates that active lighting, when strategically positioned, improves bicyclists' conspicuity at night. Road cyclists are unique among other vulnerable road users in two ways: 1) they can leverage their own biological human motion *and* mechanical bicycle motion when using conspicuity solutions; 2) their visual surface area shown to approaching traffic is greater when viewed from a right angle (i.e., 90 degrees) than from the front/rear. However, research has not yet identified how to utilize these factors to maximize conspicuity. This project investigated the conspicuity benefits of using various configurations of six LEDs on a cyclist's body and bicycle. Experiment 1 quantified participants' responses to video recordings of a nighttime drive that featured a test bicyclist. Experiment 2, a nighttime study on a closed road, quantified participants' subjective ratings of bicyclist conspicuity at night. The findings from these studies confirmed that capitalizing on drivers' sensitivity to patterns of motion can significantly enhance bicyclists' nighttime conspicuity when viewed from the side. Particularly effective is highlighting the rotating motion of a bicycle's wheels, allowing drivers to quickly and easily identify bicyclists.

DEDICATION

This dissertation is dedicated to my mother, Lori, and my father, Brian, whose unwavering love and support allowed me to see this journey through to completion.

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First and foremost, I want to express my deepest gratitude to my advisor and friend Dr. Rick Tyrrell. He motivated me to push forward and succeed in my 6 years of graduate school, even when I faced seemingly insurmountable challenges. Rick, I'm proud of the scientist that you helped me become. Keep being awesome!

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Dr. Michael Boyce, you inspired me to pursue a career in human factors psychology and I am thankful for your support and encouragement as I chose my path through graduate school. You continue to be someone I look up to and strive to emulate in personal and professional life.

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CHAPTER ONE

INTRODUCTION

In 2015, motor vehicle crashes killed 818 cyclists and injured an additional 45,000 in the United States (National Center for Statistics and Analysis, 2017). The risk posed to cyclists and other vulnerable road users is even greater worldwide, with an estimated 1.2 million killed in traffic crashes each year (World Health Organization, 2009). Cyclists are particularly vulnerable when sharing the road with motor vehicles at night, according to a recent analysis of Dutch traffic crash data, citing a greater injury rate in darkness than in daylight when controlling for distance traveled (Twisk & Reurings, 2013). Similarly, Czech cyclists faced the greatest risk of dying in a crash with a motor vehicle when riding on roads without streetlights at night (Bíl, Bílová, & Müller, 2010).

A major causal factor in these crashes is the reduced ambient illumination in the nighttime roadway environment (Owens & Sivak, 1996). A growing body of psychophysical research demonstrates the human visual system's degraded performance in low illumination (i.e., scotopic and mesopic) conditions relative to photopic lighting conditions. For example, a recent review (Tyrrell, Wood, Owens, Whetsel Borzendowski, & Stafford Sewall, 2016) highlighted how low lighting conditions negatively impact visual acuity (Johnson & Casson, 1995; Arumi, Chauhan, & Charman, 1997), contrast sensitivity (Peli, Arend, & Labianca, 1996), motion perception (Gegenfurtner, Mayser, & Sharpe, 2000), and color sensitivity (Pokorny, Lutze, Cao, & Zele, 2006) of visually healthy (or corrected-to-normal) adults. Interestingly, a number of studies have shown that the lighting transition seen during civil twilight, in which photopic daylight shifts to mesopic functioning, can dramatically reduce visual performances (Owens, Francis, & Leibowitz, 1989). Thus the effect of low illumination on the human visual system means that low contrast hazards like cyclists can easily go unnoticed by drivers until it is too late to ensure that drivers can prevent a collision. In other words, at night cyclists are too often insufficiently conspicuous to motorists.

Fortunately, research has uncovered ways for cyclists and other vulnerable road users to improve their nighttime conspicuity to motorists. Beginning in the 1970s, Swedish perceptual scientist Gunnar Johansson researched humans' perceptual sensitivity to biological motion ("biomotion"). Biomotion is a pattern of body movement that creates a visual stimulus uniquely identifiable as a biological organism in motion (Johansson, 1973; Blake & Shiffrar, 2007). Humans are particularly gifted in recognizing human biomotion and can even do so from infancy, which suggests a biological predisposition to this skill (Simion, Regolin, & Bulf, 2008). These findings from basic perceptual science were later applied to improve the conspicuity of vulnerable road users like pedestrians and bicyclists (Owens, Antonoff, & Francis, 1994; Tyrrell, Wood, Owens, Whetsel Borzendowski, & Stafford Sewall, 2016; Wood, et al., 2012).

Perceptual scientists and transportation safety researchers continued to expand upon these initial findings in a series of noteworthy studies. Kwan and Mapstone (2004, 2009) have reviewed much of this literature already – including research on bicyclist and pedestrian visibility both in daylight and nighttime – which demonstrated this topic's importance in transportation safety. Kwan and Mapstone emphasized one notable finding in their meta-analyses and literature reviews: there is not one single ‘best’ conspicuity solution for every roadway situation (or even a majority of them). The numerous lighting conditions, traffic layouts, and driving behaviors found worldwide necessitates an empirical approach to bicycle safety; the potential safety benefits of a bicyclist conspicuity solution depends entirely on the situation in which it is used. However, one thing remains clear: efforts to enhance bicyclist conspicuity that involve highlighting the rider’s biological motion will be more effective than those that do not (Blomberg, Hale, & Preusser, 1986; Wood, et al., 2012).

One notable study of nighttime bicyclist conspicuity, published after the Kwan and Mapstone review papers, examined younger and older drivers’ ability to recognize bicyclists on a closed-road while driving an instrumented vehicle at night (Wood, et al., 2010). Confederate cyclists pedaling on stationary bicycles in two different roadside locations donned one of four garment configurations – one of which was a black track suit, plus a standard safety vest, plus small retroreflective bands around the ankles and knees to create a modified biomotion configuration. Experimenters also manipulated the orientation of the test cyclist relative to the heading of the participants’ approaching test vehicle – participant drivers saw either the rear (0 degrees) or side (90 degrees) of the test cyclist when passing – though the side-view manipulation is most relevant to the current proposed study. Ultimately, a significantly larger percentage of drivers (90%) were able to correctly recognize the presence of the bicyclist in the modified biomotion configuration compared to the three apparel configurations that did not incorporate biomotion. Further, this simple addition of retroreflective bands around the ankles and knees demonstrated nearly a 40% increase in the frequency of correct responses from both younger and older drivers' relative to the otherwise-identical vest configuration. This study currently offers the best insight into real-world nighttime conspicuity of bicyclists who are viewed perpendicularly.

However, Wood, et al., (2010) were not the only researchers to successfully study the conspicuity benefits of highlighting a rider's biological motion in a road setting outdoors. Edewaard, Fekety, Szubski, and Tyrrell (2016) conducted an open-road study of the conspicuity benefits of fluorescent cycling apparel in daylight. These researchers drove participants along a pre-determined route and asked them to press a button whenever they were confident that they identified a cyclist in or near the roadway ahead. Approximately half-way through their 15-minute trip, participants encountered an experimenter pedaling on a stationary bicycle (the test vehicle approached the cyclist from behind) while wearing one of four apparel treatments – two of which included fluorescent yellow leggings in addition to a fluorescent jersey. By keeping the test vehicle at a fixed speed while approaching the test cyclist, these researchers were later able to convert participants' response times (recorded from their button presses) into response distances. Surprisingly, mean response distances to the cyclist wearing all-black apparel were not significantly different from those for the cyclist while wearing a fluorescent yellow jersey on top of the all-black outfit. However, the cyclist wearing fluorescent yellow leggings (highlighting the pedaling motion of the rider's legs) in addition to the fluorescent jersey increased participants' mean response distances by 3.3 times relative to an identical cycling outfit with black leggings instead of fluorescent yellow. In fact, these leggings retained their conspicuity advantage even when they had a half-fluorescent-yellow and half-black checkerboard pattern instead of solid yellow. Ultimately, this study of fluorescent apparel was the first of its kind to be conducted in daylight on U.S. roads, and offers valuable insights into participants' reactions to roadway cyclists in unexpected locations.

Several studies have addressed the bicyclist conspicuity problem by asking participants to make subjective judgments of conspicuity. One experiment targeted the differences between cyclists' perceptions of their conspicuity compared to the actual distance from which drivers recognized the presence of a cyclist (Wood, Tyrrell, Marszalek, Lacherez, & Carberry, 2013). These experimenters asked participants to wear multiple lighting and apparel treatments on the side of a closed road at night, while estimating the distance from which a driver would just be able to recognize them as a bicyclist (i.e., the recognition threshold distance). Participants' estimations were later compared with participant drivers' actual recognition distances in the same environment and cyclist lighting/apparel treatments. On average, the bicyclists perceived themselves to be more recognizable to drivers than they actually were in every lighting and apparel configuration. The only exception to this was when participant bicyclists wore a fluorescent and retroreflective vest plus retroreflective bands around their ankles and knees; these bicyclists' estimates of their own recognizability were dramatically underestimated relative to drivers' actual recognition distances. While this demonstrates that the benefits of using biological motion apparel can potentially exceed the expectations of those wearing the garments, it also suggests that riders may not be motivated to wear biomotion markings since they appear to be unaware of their beneficial impact.

Tyrrell, Fekety, and Edewaard (2016) later asked observers to make judgments (on a 1-100 scale) of the conspicuity of experimenter cyclists pedaling on stationary bicycles in daylight. The observers' stationary test vehicle was positioned 50 meters, 100 meters, and 200 meters away from the test cyclists, who were displaying various configurations of red LED bicycle taillights. These experimenters systematically manipulated the placement, intensity, and operational mode of their bicycle taillights while participants made their conspicuity judgments. Participants consistently rated bicyclists with lights on their ankles (filtered to half-luminance relative to the single-LED configurations) as more conspicuous than those with lights in other positions, showing the importance of highlighting riders' biological motion in daylight. Additionally, participants also judged riders with flashing taillights on the seat post to be more conspicuous than those displaying steady, always-on lights in the same location. Wood, Marszalek, Lacherez, and Tyrrell (2014) successfully used similar survey methods in a study focusing on the nighttime conspicuity of road workers with retroreflective markings, while also reinforcing the growing body of empirical evidence favoring biological motion configurations to improve conspicuity.

The research methods chosen for a given bicyclist safety study can have a substantal impact on its external validity. For example, naturalistic approaches to studying bicyclist conspicuity on the open road offer valuable insights into safety issues that cannot be reliably produced in controlled lab settings. However, it is often exceedingly difficult to conduct a realistic open road experiment while maintaining sufficient experimental control to allow solid conclusions. Thus, other research methods have proven to be both useful and necessary. Such methods include showing participants pre-recorded videos of realistic traffic scenarios (Stapleton & Koo, 2017), asking road users to provide subjective conspicuity evaluations while watching bicyclists pedaling on a closed road (Tyrrell, Fekety, & Edewaard, 2016), or having them imagine and respond to stimuli based on prompts from experimenters in a laboratory (Wood, Lacherez, Marszalek, & King, 2009). For example, Wood, et al., (2009) asked participants to make subjective visibility ratings of a hypothetical bicyclist using different configurations of high-visibility apparel and lighting. Interestingly, drivers and cyclists both judged retroreflective and active lighting configurations on a rider's major moving joints as less visible at night than a standard fluorescent or retroreflective vest. However, a later study of nighttime bicyclist conspicuity, using video recordings instead of an imaginary stimulus, elaborated upon the findings reported in this report. Koo & Huang (2015) asked participants to watch a series of short videos, depicting a first-person view of a nighttime drive, each of which included passing a bicyclist who was on the right shoulder of the roadway. These videos showed the car passing the bicyclist from behind, thus participants only saw a rear-view of the riders. Participants rated four different parameters related to the bicyclist's visibility after viewing the series of videos. The authors found that participants' ratings of visibility were greatest when the bicyclist wore small magnetic LEDs on the hips, knees, and ankles; this quasi-biomotion lighting configuration proved more effective than any of the study's 'upper body' lighting configurations, as well as the hips, knees, or ankles individually. These findings were later corroborated with evidence from a follow-up nighttime bicyclist conspicuity study (Stapleton & Koo, 2017) which used eye-tracking technology to help identify drivers' fixations and dwell times coinciding with the appearance of test bicyclists in clothing conditions similar to the 2015 study. Together, these studies demonstrate the conspicuity benefits of highlighting the moving joints of a rider's lower body at night (i.e., biomotion).

As previously mentioned, other studies of pedestrian conspicuity have also successfully used video-based research methods similar to those detailed in Koo & Huang (2015). Owens, Antonoff, and Francis (1994) showed participants a series of short videos depicting a first-person view of a nighttime drive, and instructed them to step on a simulated brake pedal each time they recognized a jogger near the road. In the second of the two experiments published in this study, participants simultaneously used a joystick to perform a secondary visual tracking task – researchers did this in order to divide participants' visual attention between two tasks during testing. The authors calculated their primary dependent variable (reaction time) by recording the time elapsed between the initial brake depression and 'passing' the jogger. On average, retroreflective configurations making use of the jogger's biological motion elicited faster recognition response times (i.e., participants recognized joggers from farther away) than retroreflective vest configurations or retroreflective bands positioned on areas other than the major moving joints. Later, Moberly and Langham (2002) instructed participants to press a button upon detecting any roadside pedestrians in a pre-recorded video of a nighttime drive. Ultimately, the authors failed to observe a significant effect of apparel highlighting the wearer’s biomotion; interestingly, this is the only documented non-significant finding of the effect of biological motion on pedestrian conspicuity. However, the likely cause of this negative finding has since been identified as low statistical power and potential confounding variables in the experimental design, unrelated to the study’s chosen video-based methods (Langham & Moberly, 2003; Tyrrell, et al., 2009). Regardless, the methods used in these reports (Koo & Huang, 2015; Owens, Antonoff, & Francis, 1994; Moberly & Langham, 2002) together demonstrate the high potential value of pre-recorded video stimuli in experimental studies of conspicuity, especially when researchers take steps to ensure the video-based methods create a more ‘realistic’ roadway experience for participants, e.g., carefully calibrated video images, secondary attention tasks.

Unlike pedestrians, the visual appearance of a bicyclist at a distance is much less ‘human-like’ due to the rider’s posture, their bicycle underneath, and their movements being constrained by the mechanics of the bicycle. The visual forms generated by a moving rider on their bicycle are both biological and mechanical in this regard. Fortunately, research has shown that conspicuity treatments can also be effective when strategically placed on the mechanical components of the bicycle itself despite humans’ inherent ability to recognize biological motion. In fact, the National Highway Traffic Safety Administration (NHTSA) recommends bicyclists use a front and rear light (mounted to the handlebars and seat-post, respectively) while riding at night, but does not yet offer any official recommendations for ways that bicyclists can remain visible when viewed perpendicularly (National Center for Statistics and Analysis, 2017). However, one American study (Burg & Beers, 1978) found that retroreflective bicycle tire sidewalls improved drivers' ability to recognize stationary and moving bicyclists when viewed from a perpendicular angle at night when compared with the standard wheel spoke reflectors of the time. Similarly, a British study (Watts, 1984) found that bicyclists with rear-facing active lighting or reflectors mounted to their bikes were detected sooner than those without, even in the presence of oncoming headlight glare.

More recently, a series of studies of bicyclist visibility – in which researchers strategically applied reflective tape to the frame of a bicycle rather than the cyclists themselves – demonstrated the value of highlighting both moving and non-moving types of mechanical bicycle components when observers/drivers approach a cyclist from behind (Costa, et al., 2017). Depending on which one of the four studies participants signed up for, researchers instructed them to respond either when detecting an obstacle ahead (this was always the test bicyclist) or when recognizing that an obstacle was a bicyclist. Specifically, these studies concluded that reflective tape applied to either the seat post, left and right seat stay, a rear-mounted cargo rack, or pedal crank arm can each significantly improve drivers' ability to recognize the cyclist from farther distances. Interestingly, the authors also found that certain conspicuity solutions – such as reflective tape on the seat post, seat stay, and rear cargo rack – can increase drivers' detection distance nearly twofold when viewing the rear of the cyclist even in active (but mild) precipitation at night.

However, little research exists on the conspicuity of bicyclists who are viewed from the side (i.e., perpendicularly, as if crossing a street at a right angle to approaching traffic). The notable exceptions are the previously discussed papers by Wood, et al. (2010) and Burg & Beers (1978). This is somewhat unsurprising, since many estimates show that bicyclists are at greatest risk of being killed or seriously injured in a bicycle-car collision while traveling in the same direction as traffic, i.e., hit from behind (Kim, Kim, Ulfarsson, & Porrello, 2007; Stone & Broughton, 2003). However, other sources (e.g., Räsänen & Summala, 1998) have identified side-impact bicycle-car collisions at street crossings as a serious and substantial risk due to their unique human factors challenges. For example, drivers traveling through an intersection may have a lowered expectation for encountering a bicyclist entering the roadway, the bicyclist may be visible for only a limited time before entering a driver's path, or each party's failure to notice the other one as a hazard before a collision can all be contributing factors. There may be a greater opportunity to improve the conspicuity of bicyclists who are viewed from the side compared to a rear-view or frontal-view because a bicyclist viewed at a right angle displays a greater surface area with more moving components. In other words, a bicyclist viewed from the side displays more 'real estate' with which to highlight dynamic visual information to an approaching driver.

Encouraging findings from pedestrian safety studies, which often tackle similar conspicuity issues as those seen with bicyclists, suggest that the greater surface area on a bicycle viewed from the side may offer important conspicuity advantages that are as yet uninvestigated in the literature. Specifically, numerous studies of pedestrian safety research – which happen to involve highlighting biological motion to improve conspicuity – suggest that 'more is better,' i.e., highlighting a greater amount of a person's major moving joints increases the likelihood of identification (Tyrrell, Wood, Owens, Whetsel Borzendowski, & Stafford Sewall, 2016), and it stands to reason that this finding should apply to bicyclists as well. Given that a driver's ability to recognize a bicyclist is not significantly impacted by the direction in which the rider is facing (Wood, et al., 2010), and that approximately 28% of bicyclist fatalities in traffic are the result of being struck an intersection or road crossing (National Center for Statistics and Analysis, 2017), investigations into bicyclist conspicuity from a side-view orientation can offer additional opportunities to advance bicycle safety. Granted, traffic crash statistics like these can only imply (rather than prove) the prevalence of side-impact crashes relative to front- or rear-impact. However, it is reasonable that the complex traffic patterns, lights, and signage found at intersections could often co-occur with side-impact crashes like ones simulated in the current study.

Thus there is a need to expand the literature pertaining to bicyclist conspicuity when viewed from the side at night. There is an unanswered question of whether the rider's own body or the mechanical components of a bicycle afford the greatest opportunity to maximize conspicuity when using strategically positioned active lighting solutions. A key consideration in this comparison is the fact that humans possess a perceptual sensitivity to biomotion (e.g., active lighting highlighting the rider's body parts), but little is known about whether the dynamics of the bicycle's movements can be just as salient and identifiable when adorned with active lighting. With regards to this point, it is also noteworthy that humans' perceptual sensitivity to biomotion is likely an evolved skill, yet it is unlikely that humans possess an inherent perceptual sensitivity to the motion of bicycles. An empirical approach to this research question can offer insight into the potential effectiveness of positioning multiple bicycle lighting solutions in nontraditional areas (such as the rider's legs or the bicycle's wheel spokes) while considering a rider's consistently-changing pedaling engagement with the bicycle. In other words, optimal bicyclist conspicuity designs must be effective both when a rider is pedaling their bicycle and while 'coasting' (i.e., moving forward without pedaling). To my knowledge, the coasting issue has not yet been addressed by roadway conspicuity researchers.

The current project involved two experiments that investigated the side-view conspicuity of bicyclists at night. The side-view perspective in this study is meant to approximate that of a driver encountering a bicyclist who is crossing a street at a perpendicular angle to the driver's path. The primary purpose of this project is to test the conspicuity enhancing potential of a series of patterns of active lights that are strategically positioned on a bicyclist and/or the bicycle. A secondary purpose of the project is to examine the conspicuity benefits of these bicycle lights' relative to reflective elements configured in the current United States legal standard for bicycles. In the first experiment, participants actively searched for bicyclists within a series of pre-recorded videos depicting a driver's view of a nighttime trip. A single rider crossed the vehicle's path while displaying one of twelve different lighting configurations. In half of the videos the test rider was pedaling at a consistent cadence, and in the other half the cyclist was ‘coasting’ with no pedaling but traveling at the same speed. I measured participants’ reaction times to this test bicyclist (as well as other trials showing non-bicyclist road users and ‘decoy’ hazards). Participants in the second experiment provided subjective conspicuity ratings of a stationary bicyclist seen from different observation distances. This rider displayed one of five different active lighting configurations or a reflector configuration) – a subset of conditions from the first experiment – while pedaling on a stationary bicycle on a closed roadway at night.

I hypothesize that a bicyclist’s conspicuity can be enhanced by the application of active lighting, and that not all lighting configurations affect conspicuity equally. More specifically, multiple lights positioned on the bicycle’s wheel spokes should maximize a rider’s conspicuity in both experiments, due to the fact that this lighting configuration retains its dynamics regardless of whether the bicyclist is pedaling or coasting. Similarly, it seems unlikely that a rider displaying lights on their bicycle wheels would be mistaken for a pedestrian. After all, while it is important for cyclists to be visible (i.e., detectable) it is better for them to be correctly identified/recognized as cyclists and not as a different type of road user or hazard. In contrast, lighting configurations highlighting the movements of the rider’s major joints (e.g., the ankles, knees, and hips of the lower body) require the rider to continue pedaling in order to present drivers with a comparably dynamic and identifiable visual stimulus. In both experiments, it was expected that the separate lighting configurations highlighting the unmoving joints of the bicycle’s frame and the rider’s upper body would be less conspicuous than the aforementioned lower body and wheel spoke configurations. Together, the results of these two experiments were meant to demonstrate the nighttime conspicuity advantages (if any) of multiple, strategically positioned bicycle lights when they are used to highlight dynamic components of a rider's body or bicycle. I expected the findings from these experiments to inform manufacturers' future design choices for active lighting products, as well as providing riders with an empirically based approach to maximizing their own conspicuity at night.

CHAPTER TWO

EXPERIMENT ONE: METHOD

Participants

Fifty-three (53) undergraduate students received course credit for participating in this experiment. I calculated this sample size based on a power analysis using the following estimated parameters in G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009): $\alpha = 0.05$; power = 0.8; effect size $f(V) = 0.58$. All participants were required to have a valid driver's license in order to take part in this study. Participants' vision was screened to ensure a minimum 20/40 corrected binocular visual acuity (Bailey-Lovie), a minimum binocular log contrast sensitivity score of 1.65 (Pelli-Robson), and no self-reported visual pathologies other than corrected refractive errors. Thirty-six of the participants were female and the mean age of all participants was 19.2 years old.

Design

The experiment followed a two (Pedaling) by six (Light Placement) factorial design. The dependent variable is response time: the duration that separates the participant's response from the moment the bicyclist first became visible. Pedaling and Light Placement were manipulated within-subjects to ensure that each participant experienced all possible experimental configurations during their session. The two levels of the Pedaling variable are Pedaling and Coasting. The six levels of Light Placement are Control, Legal Control, Bike Frame, Upper Body, Spokes, and Lower Body. See Table 2.1 and Figure 2.1 for details about each experimental configuration.

Table 2.1 Experimental bicycle light manipulations.

Independent Variable	Configuration	Description
Pedaling	Pedaling	The test bicyclist is traveling at 13 km/h (8 mph) while actively pedaling at 60 rpm.
	Coasting	The test bicyclist is traveling at 13 km/h (8 mph) with his body in a fixed, unmoving riding position.
Light Placement	Control ('CNTRL')	No lights or reflectors visible on the bicycle.
	Legal Control ('LEGAL')	A bicycle with all legally-required reflectors visible: a silver front-facing reflector on the handlebars, a red rear-facing reflector on the seat post, amber colored reflectors on each pedal, and silver spoke-mounted reflectors on each wheel. No active lighting visible on the bicycle or test bicyclist.
	Bike Frame ('FRAME')	Six lights total; no reflectors visible. One light positioned at the left end of each of the test bicycle's front and rear wheel axles, the front and rear end of the downtube, and at the front and middle of the seat stay.
	Upper Body ('UPBOD')	Six lights positioned on the test bicyclist's right and left wrists, left elbow, left shoulder, left upper hip, and left side of the helmet, all facing the camera. No reflectors visible.
	Spokes ('SPOKE')	Three lights positioned on the spokes of each wheel, approximately half-way between the center axle and the wheel rim, each separated by approximately 120 degrees. No reflectors visible.
	Lower Body ('LOBOD')	Six lights positioned on both of the test bicyclist's ankles, knees, and upper thighs, all facing the camera. No reflectors visible.

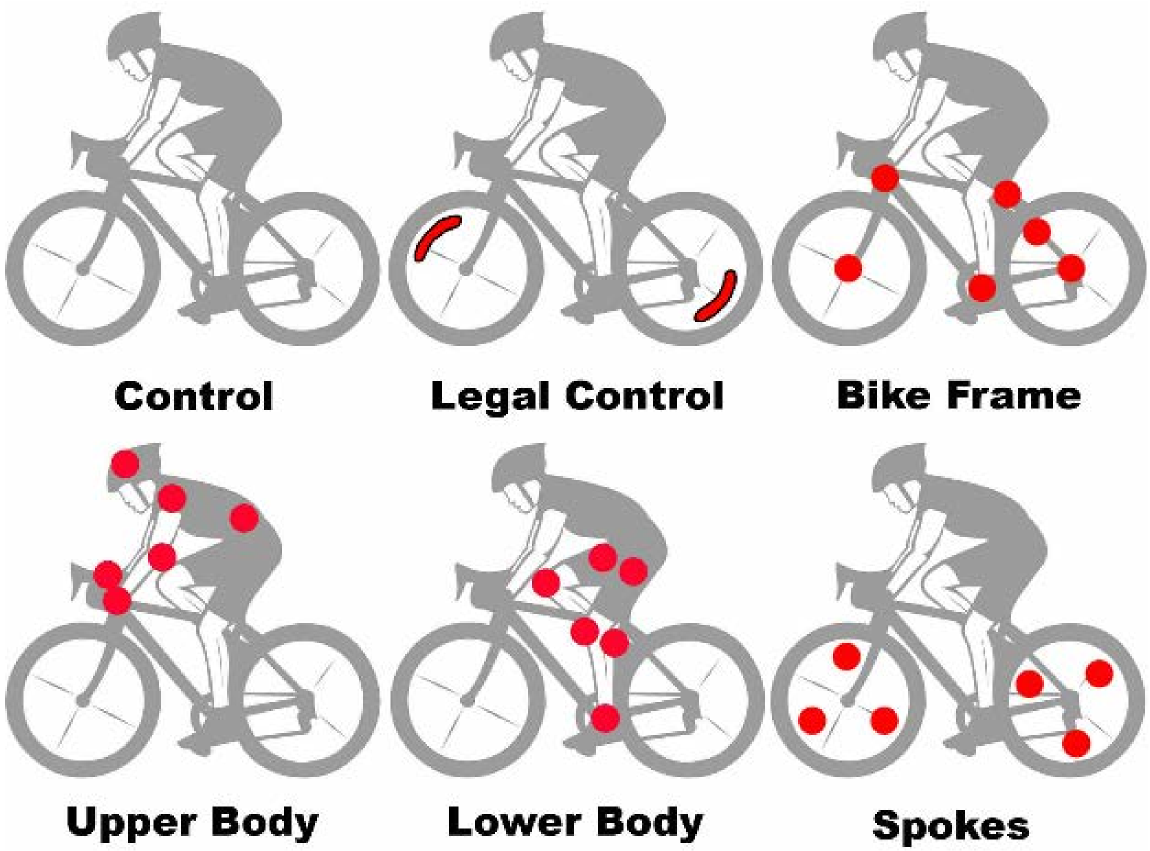


Figure 2.1 The six levels of light placement. Red dots indicate LED placement locations, except for Legal Control (in which red shapes on the wheels represent standard reflector placement).

An important point must be made with regard to the inclusion of, and specifications for, the Legal Control configuration. The United States legal requirement for bicycle reflectors (introduced in 1978 and current as of 2018) states that reflective tire sidewalls and/or reflective wheel rims may be used “in lieu of spoke-mounted reflectors,” and that these materials must “form a continuous circle” when illuminated and viewed from the side (Requirements for reflectors, 1978). However, the pattern of visual information conveyed by a bicyclist in motion would be much different between spoke reflectors and tire sidewalls / wheel rims. For the purpose of this study, traditional spoke reflectors (one on each wheel, collectively displaying approximately 4,840 mm^2 in reflective surface area to observers) were chosen for their appearance as a series of illuminated nodes of reflected light moving in circles as the wheels rotate. In contrast, an illuminated continuous circle of reflective material on the tire sidewall or wheel rim would convey less dynamic visual information (translation but not rotation) about the motion of a bicyclist relative to the spoke reflectors that are more commonly seen on roadways in the United States. Therefore, the pattern of motion highlighted by this study's Legal Control configuration offers the most typical motion information among the legally-allowed options for wheel-mounted bicycle reflectors in the U.S.

Materials

The video recording site was Hugo Drive, a two-lane service road near the university campus (see blue line in Figure 2.2). This road features a 289 m straight section, which leads to a dead-end cul-de-sac in an industrial park (see Figure 2.3). The speed limit on this section of road is 30 mph.

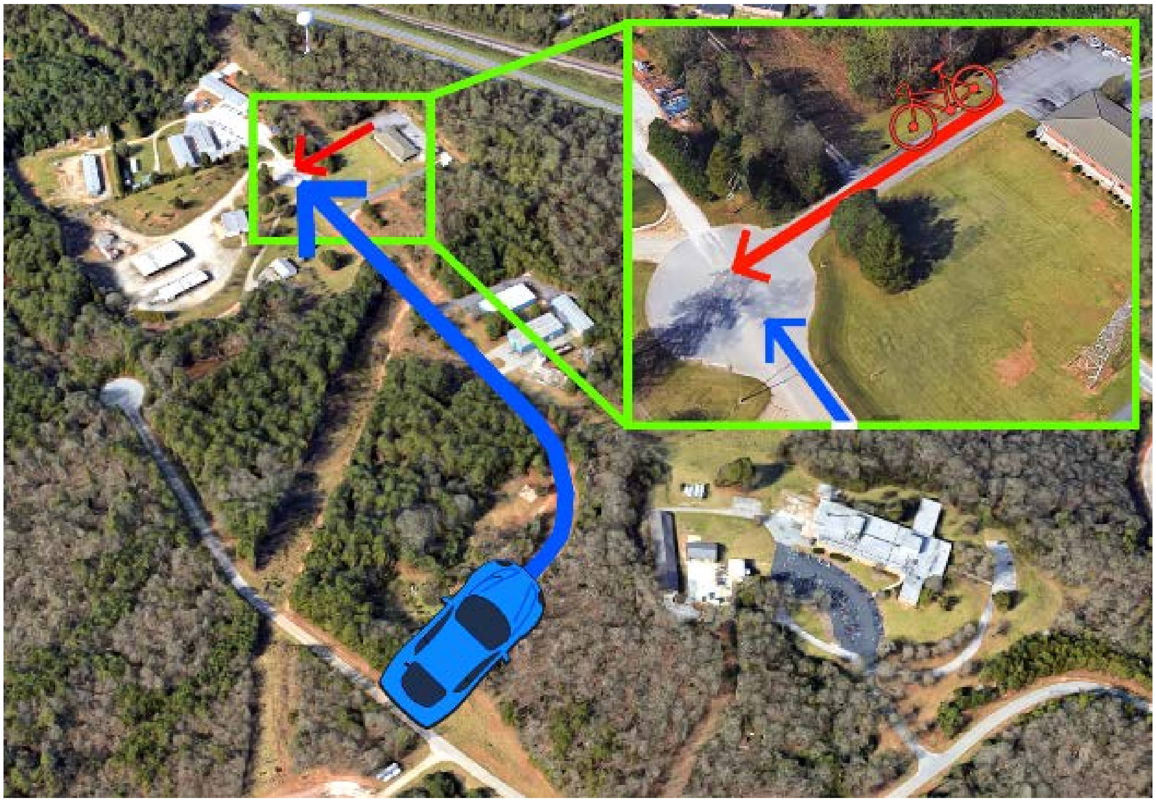


Figure 2.2 A satellite image of the service road used to record the video stimuli for Experiment 1. The blue arrow on the map highlights the path of the test vehicle and the red arrow highlights the path of the test bicyclist.

Figure 2.3 The top photo shows a daytime view from the driver's perspective at a distance of 289 m. The bottom photograph shows a magnified view of the intersection with an approaching vehicle and an experimenter standing with a bicycle to the right side of the intersection.

An experimenter acting as a bicyclist used a black bicycle (Trek 7.3 FX 17.5; Model 1327010-2016). Experimenters mounted a bicycle computer (Bontrager Trip 300 and Duo Trap S) to the test bicycle to ensure consistent speed (approximately 13 km/h or 8 mph) and cadence (approximately 60 rpm when pedaling). By monitoring this bicycle's real-time speed and cadence information during video recording sessions, the test bicyclist reduced the possibility of speed and cadence acting as confounding variables in the experiment. Experimenters removed the test bicycle's chain from the drivetrain for an additional layer of experimental control. This strategy, combined with the test bicyclist's method of approaching the target intersection from a downhill slope in order to gain momentum, meant that the test bicyclist's pedaling did not produce power and his travel speed remained consistent for both Pedaling and Coasting conditions.

The test bicyclist wore an all-black outfit (including a helmet, jersey, arm covers, shorts, knee covers, gloves, socks, and shoes) for the entire duration of each session. Experimenters removed or temporarily covered all distinctive logos, designs, and reflectors on this test bicycle before video recording (with the exception of the reflectors necessary for the Legal Control configuration's appearance).

The test bicyclist placed a set of six small magnetic LEDs (see Figure 2.4) in the locations outlined in this study's experimental design (Table 2.1 and Figure 2.1). These products, known commercially as 'Lucina,' are produced by Palomar S.r.l. (Florence, Italy). These lights each produce 15,000 mcd (according the manufacturer's specifications) and are powered by two disposable CR2032 lithium cell batteries. The circular lensing measures 3 mm in diameter (42 mm^2 of lensing for the set of six) and houses a single white LED in the center. The lensing evenly distributes the device's light across a wide conical beam so as to be visible from a large range of observation angles. A small magnet mounted to the back of each light is used to mount onto various locations on the rider's body/bicycle, and a threaded tether ensures that the light can stay in its intended place if the magnets lose contact with each other while in motion.

Figure 2.4 Lucina lights, shown in the off state with the magnetic backing attached (top) and the light turned on with the magnetic backing separated (bottom).

The stimuli used for this experiment are a series of 26 short video clips (each 35 seconds in duration) of a nighttime drive, taken from the perspective of a driver in a moving vehicle traveling towards the intersection seen in Figures 2 and 3. These stimuli were recorded on a night free from precipitation and fog, at a time when 37% of the moon's visible disk was illuminated and visible to the left of the driver's perspective (west-south-west of the target intersection). Video segments were recorded using a Nikon D3200 DSLR camera (with AF-S DX Zoom-NIKKOR 55-200mm f/4-5.6G ED lens) mounted to a tripod and positioned in the middle rear seat of the test vehicle – a 2015 Audi A6 Prestige with LED headlamps. Prior to recording the video stimuli, experimenters calibrated the camera using the following settings: F5.6 aperture; ISO 12800 ('high'); 1/8 shutter; 1920 x 1080p image resolution; auto white-balance; 30 frames-per-second. The focal length of the lens was calibrated by manually adjusting the 18 mm – 55 mm lens until the apparent size of objects (e.g., experimenters in the road, street signs, roadway markings) seen with the right eye through the viewfinder matched that of the same objects seen through the left eye without the viewfinder. See Figure 2.5 for an example still image from the recording of the video calibration session. Videos were later up-scaled to a resolution of 2560 x 1440p and 60 frames-per-second with Adobe Premiere Pro CC 2017 software.

Figure 2.5 A still image taken from the recording of the camera calibration session, which took place at Hugo Drive. Three researchers – one of which was holding a Pelli-Robson contrast sensitivity chart – stood in front of the test vehicle while experimenters in the vehicle calibrated the camera's video settings. Experimenters in the test vehicle adjusted the camera's settings until the contrast and color characteristics of the video matched what could be seen by the eye.

Each video segment depicts the same driving approach to the video recording site's intersection/cul-de-sac (for example screenshots from the video stimulus set, see Appendix A). One subset of these video segments (referred to as *bicycle* trials, 12 total) shows the test bicyclist crossing the street from right to left in front of the test vehicle, perpendicular to the car's path of travel. The remaining video segments (termed *distractor* trials, 14 total) show various roadway objects/hazards, which are not directly relevant to the study's hypotheses, described in Table 2.2 below. The only noticeable difference among the subset of 12 bicycle trials is the positioning of the test bicyclist's magnetic lights. In the bicycle trials, the test bicyclist approached the target roadway intersection by riding on a downhill slope, reaching the target travel speed while still invisible to the approaching car, and then carrying momentum through the intersection. The test bicyclist maintained a consistent traveling speed during this time by monitoring the bicycle computer displaying speed information in real-time. The information displayed on the backlit bicycle computer display was not visible to observers in the approaching test vehicle.

Table 1.2 Distractor trial descriptions (14 in total).

Distractor trial name	Distractor trial description
Blank	A drive-by with no other visible road users or hazards present.
Bicycle decoy	A drive-by in which the test bicyclist, wearing a headlamp and retroreflective bands on each ankle, rides towards the test vehicle in the opposing lane of traffic.
Pedestrian with biomotion (x2)	A drive-by in which one pedestrian, wearing magnetic lights (Figure 2.4) and retroreflective bands on their ankles is visible walking on the shoulder of the road. Two videos were made for this condition, showing the pedestrian on the left and right shoulders of the road.
Pedestrian crossing with biomotion	A drive-by in which one pedestrian, wearing a retroreflective vest and pants, is visible walking across the intersection from right to left, perpendicularly to the test vehicle’s path of travel, along the same path as the test bicyclist in the bicycle trials.
Group of joggers (x2)	A drive-by in which a group of three pedestrians, in high-visibility vests and retroreflective bands on their ankles, are visible jogging on the shoulder of the road. Two videos were made for this condition, showing the joggers on the left and right shoulders of the road.
Group of joggers crossing	A drive-by in which a group of joggers, wearing various configurations of high-visibility apparel, are visible walking across the intersection from the right, perpendicularly to the test vehicle’s path of travel, along the same path as the test bicyclist in the bicycle trials.
Pedestrian with plain clothes (x2)	A drive-by in which one pedestrian, in low-contrast non-reflective apparel, is visible walking on the shoulder on the road. Two videos were made for this condition, showing the pedestrian on the left and right shoulders of the road.
Light post (x2)	A drive-by in which a pole sticking out of a traffic cone, adorned with several magnetic lights, is visible on the shoulder of the road. Two videos were made for this condition, showing the light post on the left and right shoulders of the road.
Automobile approaching from the right	A drive-by in which an automobile is visible approaching the intersection from the right, perpendicularly to the test vehicle’s path of travel, along the same path as the test bicyclist in the bicycle trials.
Automobile oncoming	A drive-by in which an automobile is approaching the test vehicle from the intersection in the opposing lane (i.e., oncoming traffic) using its low beam headlamps.

All 26 video recordings were edited to be the same duration (35 seconds) via Adobe Premiere Pro. Each of the videos began one frame after a retroreflective traffic cone (which was intentionally placed on the shoulder of the road for the video recording night) disappeared from the camera's view; this ensured that each video began at the same landmark in the roadway.

In each of the 12 bicycle trial videos, I measured the first and last frames in which the test bicyclist was visible and used these reference points to calculate the total number of frames in which the test bicyclist was visible (see Table 2.3). It was not possible to determine the first frame in which the Control-Pedaling and Control-Coasting bicycle conditions appeared (due to low contrast between the bicyclist and the dark roadway background). Instead, I substituted this value with the mean first-frame-number of each of the other ten bicycle trials (i.e., frame number "1828.6").

Table 2.3 Timestamps (in frame numbers) for the first and last moment in which the test bicyclist is visible in each video recording, as well as the total number of frames in which he is visible. There are 60 frames per each second of video.

Bicycle trial name	**First visible frame**	**Last visible frame**	**Total frames visible**
Control Pedaling	1828.6*	2091	262.4
Control Coasting	1828.6*	2109	280.4
Legal Control Pedaling	1823	2109	286
Legal Control Coasting	1833	2111	278
Bike Frame Pedaling	1802	2091	289
Bike Frame Coasting	1865	2121	256
Upper Body Pedaling	1856	2119	263
Upper Body Coasting	1821	2103	282
Lower Body Pedaling	1766	2074	308
Lower Body Coasting	1831	2105	274
Spokes Pedaling	1854	2121	267
Spokes Coasting	1835	2119	284
Mean (SD)	**1828.60 (26.12)**	**2106.08 (14.51)**	**277.48 (14.23)**

In contrast, I choreographed the distractor video trials so as to vary each hazard/object's entrance and exit timestamps, as well as their positioning in/near the roadway. The purpose of this was to reduce the possibility that participants would come to expect one type of object or hazard in the same position or movement pattern repeatedly, encounter a hazard at an approximate time or landmark within each video, or encounter a hazard after an approximate amount of time passed in each new video. These distractor video trials made up 60% of all video trials shown to participants. This percentage includes the repetition of the same 'Blank' video trial five times in each participant appointment, so as to increase the ratio of distractor trials to bicycle trials (bringing the total number of videos shown per participant session to 30).

Participants observed video stimuli on an iMac desktop computer with a monitor measuring 27 inches diagonally (20.3 inches high by 25.6 inches wide) and displaying 5120 x 2880 screen resolution at 60 Hz. This computer's components included a 4.2GHz quad-core i7 processor, 24GB of 2400MHz DDR4 memory, and a Radeon Pro 580 graphics processor with 8GB of dedicated VRAM. The monitor's screen brightness was adjusted to its maximum setting before each appointment. Participants viewed the series of video segments through PsychoPy2 v1.85.4 stimulus presentation software (Peirce, 2007; Peirce, 2009). PsychoPy allows researchers to display a scripted series of visual stimuli to participants while collecting participants' temporally-synchronized response data using a keyboard.

Displaying the video stimuli via the computer monitor with this method allowed for participants to view a carefully-calculated approximation of the apparent size (i.e., measured in visual angle), motion, and contrast characteristics of the test bicyclist relative to how they appeared to an observer in the real-world environment at the time of recording. As such, participants observed video stimuli while seated at a desk with a chin rest, which kept participants' eyes separated from the monitor by 141 cm. This number was calculated by first measuring the real-world width of the test vehicle's lane (381 cm) and the distance between the camera lens and the end of the road lane (1626 cm) during camera calibration. Then, these width and length values were used to calculate the visual angle of the width of the road lane from the camera lens' position (13.37 degrees). Following this, experimenters measured the width of the same road lane as it appeared on the computer monitor in full-screen mode (33 cm) and used this value to calculate the viewing distance (141 cm). Similarly, the visual contrast of the video stimuli were calibrated prior to recording by using a standardized vision testing chart as a reference (i.e., Pelli-Robson). Thus, a semi-realistic view of a nighttime trip from a driver's perspective was created by using these methods of calibrating the video stimuli and standardizing participants' seating and observation positions. That said, the ways in which the depicted videos inevitably did not 'perfectly' align with reality (apparent sizes, motion, visual contrast, etc.) are applicable to the entire video stimulus set; any errors in stimulus appearance are consistent across all testing conditions (i.e., none of the videos appear any more or any less realistic than any other videos in the experiment).

Procedure

At the beginning of each testing session, an experimenter met participants in the laboratory located in McAdams Hall 304b on the university campus. Participants completed an informed consent document, provided demographic information, and were visually screened by the experimenter. One participant was tested at a time. Once the experimenter ensured a participant's eligibility, participants were asked to sit at a desk in front of the LCD monitor that displayed the video stimuli.

Following this, participants were told that they would view a series of short videos depicting a driver's perspective of a nighttime drive. Participants were instructed to press a button on a keyboard any time they identified any of several different types of hazards/objects (e.g., bicyclist, jogger, pedestrian, car) in or near the roadway ahead. Participants responded with a mechanical keyboard, modified by the experimenter, that replaced the 1, 2, and 3 number-pad keys with "C" (for 'car'), "B" (for 'bicycle'), and "P" (for 'pedestrian'), respectively. An opaque black felt overlay was placed on top of the keyboard which hid/blocked all keys other than these three and the space key. Although bicyclists are the only object for which response data are critical for this study's hypotheses and analyses, the instructions delivered to participants did not explicitly specify bicyclists as being more or less important than another type of hazard in the test. To this end, participants saw one 35-second practice video trial (before starting the sequence of 30 data collection trials) which showed a pedestrian rather than a bicyclist. This helped limit participants' expectancy bias for bicyclists when searching for hazards/objects and reduced the likelihood for participants realizing the true purpose of the experiment.

Pressing the appropriate button on the keyboard prompted PsychoPy to create a timestamp in that participant's dataset linked to the video stimulus displayed at that time. These timestamps were later used to calculate participants' response times to each video stimulus containing a test bicyclist. For example, given a video segment which is 35 seconds in duration and features a test bicyclist appearing 30 seconds into the segment, a participant response time that logged 33 seconds into a video segment would produce a response time of 3 seconds. Smaller values in the dependent variable indicate shorter responses, i.e., better performance.

Before the start of the video trials, the experimenter dimmed the lights in the windowless room and asked each participant to position their chin on a vertically adjustable chin rest. The participant then viewed the complete set of video stimuli in a randomized presentation order (which was unique to each participant). Participants viewed a total of 30 video segments, and each participant's appointment lasted approximately 45 minutes (20 minutes of which were data collection trials). Participants completed their viewing session without interruption, while the experimenter monitored progress away from the participant's sight. Upon completing the viewing session, participants were debriefed and released.

Secondary task

Participants were also responsible for remaining engaged in a secondary activity while performing their primary task of searching for hazards in the videos. This was done for two reasons: (1) to keep participants' divided attention and mental workload at levels which more closely resemble real-world driving; (2) to reduce the probability of observing a ceiling effect in participants' performance in the primary task. The secondary task was designed to be auditory and verbal, ensuring participants did not need to divide their visual attention among the primary and secondary tasks. Thus, participants experienced the secondary task by listening to auditory stimuli via over-the-ear headphones and responding verbally.

The secondary task that was used in this experiment is commonly referred to as the 'n-back' or the 'delayed digit recall.' This task has gained considerable representation in the peer-reviewed behavioral literature as a highly customizable workload/attention task that can be paired with simulated roadway environments in experiments (Mehler, Reimer, Coughlin, & Dusek, 2009; Son, Lee, & Kim, 2011).

Participants were prompted with a pre-recorded voice of a computer speaking a single-digit integer (0 through 9) every 2.5 seconds. This recording played continuously throughout data collection trials, synchronized with – but running separately from – the PsychoPy stimulus presentation protocol. Participants were instructed to repeat out loud the number that they recalled hearing just before the current one; this is known as the '1-back' level of difficulty. For an example of the correct auditory stimulus presentation paired with the correct participant response to each prompt in the 1-back task, see Table 2.4 below.

Table 2.4 Example 1-back numbers spoken by a pre-recorded voice, followed by correct participant responses for the 1-back task. Blank cells indicate that the correct response for the participant is to say nothing at that time.

Participant hears:	7	0	2	3	4	9	1	2	6
Correct response from participant:		7	0	2	3	4	9	1	2

A new list of randomly-generated integers was printed before each participant appointment, corresponding to the numbers spoken aloud for each participant (i.e., each participant experienced a different series of random numbers). To ensure participants' compliance with the dual-task scenario, an experimenter monitored the accuracy of their performance on the secondary 1-back task with an answer key during data collection trials.

All participants were given a chance to practice this secondary task without the primary task before the start of the dual-task data collection trials (approximately 2 minutes of instruction and practice). The instructions given to participants did not specify either the video task or the spoken-number task as being a higher priority. Instead, participants were informed that the experimenter would continuously monitor the speed and accuracy with which they performed both tasks.

CHAPTER THREE

EXPERIMENT ONE: ANALYSIS

Outlier trial analysis

An initial analysis of the z-scores from participants' response times indicated that participant #2's response to the Control-Coasting condition (3.05 seconds) was 3.6 standard deviations below (i.e., earlier than) the mean for that condition. Participant #2's button-press on this trial occurred at a time when the test bicyclist's appearance was still virtually indistinguishable from the dark roadway background, and a sizeable amount of time would elapse before the cyclist's silhouette would be visible in the video recording. Since this was participant #2's only button-press for that video trial, it was determined that this data point was unlikely to be a genuine response to a stimulus given the circumstances. This data point was therefore treated as a 'miss' instead.

Hierarchical linear model of response times

The overall usable data set represents 1,590 trials among 53 participants. A subset of these data is comprised of 636 bicycle trials. The remaining 954 trials come from distractor trials – whose purpose in this study were to decrease the likelihood of participants realizing the bicyclist-focused nature of the study – and are therefore not linked to any testable hypotheses. Five-hundred and forty (540; 85% of 636) of the bicycle trials featured a participant successfully identifying a bicyclist present in the video segment. In the remaining trials (approximately 15%), the participant either failed to identify an object before the video segment ended or their chosen response was incorrect/inaccurate for that trial (see Appendix B). These participants' perceptual judgments can be referred to as 'hits' and 'misses' respectively, which is common among Signal Detection Theory research when applied to visual search tasks (Stanislaw & Todorov, 1999; Cameron, Tai, Eckstein, & Carrasco, 2004; Verghese, 2001).

The fact that Experiment 1's dataset features both hits and misses has important implications for the methods used to analyze participants' responses. The traditional repeated-measures ANOVA approach cannot partition the hit and miss trials while sufficiently retaining each participant's responses to the dataset. This is because a repeated-measures ANOVA excludes missing cases listwise (instead of pairwise) which, for the present experiment, would reduce the usable dataset by 74% by excluding data from 39 of the 53 participants. In effect, any participant who failed to correctly identify a bicyclist in *any* trial would be excluded from the analysis entirely. Additionally, the within-subjects nature of the experimental design means that there is a substantial amount of nestedness among the variables because data collection trials occurred across multiple measurement occasions. Relatedly, participants' performance in a trial is impacted by the trials preceding it as trial performances are not independent of one another. This violates a critical assumption of the repeated-measures ANOVA approach which is often overlooked or unaddressed in the behavioral science literature.

According to Heck, Thomas, and Tabata (2013), multilevel modeling (also known as hierarchical linear modeling, or HLM) can be used to address the nestedness of participant trials when the intra-class correlation coefficient (ICC) exceeds 0.05 in a baseline model. Additionally, participants' performance from one trial to the next does not need to be independent to satisfy the assumptions of HLM. In the context of the present study, HLM has the benefit of accommodating predictors which vary at the measurement occasion level (called 'Level 1'; Cohen, Cohen, West, & Aiken, 2003). Additionally, HLM's flexibility as a statistical method means that the frequency of hits and misses do not need to be balanced (i.e., equally distributed) across all experimental conditions. Thus, HLM allows for measurement occasions to have a certain degree of dependency while retaining all measurement occasions, rather than discarding participants' data indiscriminately when they do not satisfy the criteria for the hypothesis test – as would be the case in a traditional repeated-measures ANOVA.

HLM's effect sizes are sometimes referred to as '*pseudo-*R^2' – a value which indexes the percentage of the variance in the model that is explained by a predictor, relative to a baseline model without that predictor. For the purpose of this study – which only includes Level 1 main effects and a Level 1 by Level 1 interaction term – the reduction in error variance indexed by R^2 is reported for significant effects only. Level 1 variables, also known as within-subjects variables, are those which change at the measurement occasion level – unlike Level 2 / between-subjects variables which change at participant-level. Further, HLM is a unique statistical method in that it is appropriate for normally-distributed data (e.g., those suitable for traditional generalized linear models) and non-normally distributed data (e.g., logistic models with hit/miss outcomes) alike. As such, the first analysis reported here relates to the participants' response times and the subsequent binary logistic regression analyses focus on participants' hit/miss outcomes.

A hierarchical linear model was created to analyze the effects of Light Placement and Pedaling (both Level 1 variables) separately predicting participants' response times across the 12 bicycle configurations. Because the dependent variable is response time, this analysis only included trials in which participants correctly identified a bicyclist in the video (i.e., hits). Based on the guidelines outlined in (Raudenbush & Bryk, 2002), a baseline (or null) model was determined for the response time DV across participants and bicycle trials. Analysis of this model revealed that 12.2% of the total variance in response times resides between participants (ICC = 0.122) and 87.8% of the total variance in response times resides within participants, which indicates the level of nestedness in the dataset is sufficient to justify the use of a mixed model approach (Heck, Thomas, & Tabata, 2013). Then, each predictor variable was added hierarchically into the model, so as to detect each predictor variable's influence on response times incrementally. Appendix C shows descriptive statistics for all of the 'hit' responses to experimental conditions (in seconds).

Table 3.1 Mean and standard deviation response times (seconds) for each experimental condition. Smaller values indicate better participant performance.

	Control	**Legal Control**	**Bike Frame**	**Upper Body**	**Lower Body**	**Spokes**	**Total**
Pedaling	4.03 (0.48)	2.46 (1.11)	2.09 (1.03)	1.90 (0.76)	2.64 (1.39)	1.68 (0.72)	2.33 (1.18)
Coasting	4.44 (0.29)	2.34 (1.02)	2.11 (0.94)	2.07 (1.00)	2.46 (1.11)	1.64 (0.56)	2.39 (1.19)
Total	4.25 (0.44)	2.39 (1.06)	2.10 (0.98)	1.99 (0.89)	2.54 (1.24)	1.66 (0.64)	2.36 (1.18)

The first model incorporated Light Placement as the predictor of response times (as both a fixed and random effect). Participant response times significantly differed across the Light Placement conditions, $F(5, 484.97) = 92.92$, $p < .001$ (see Figure 3.1), and was shown to reduce the residual variance by 48.6% relative to the baseline model (see Change in Model R^2 in Appendix D). All post-hoc pairwise comparisons (Least Significant Difference) revealed significantly different means, with the exception of the pairings of Legal Control / Lower Body ($p = .173$) and Bike Frame / Upper Body ($p = .264$). Relative to the Control configuration, participants responded significantly earlier to each of the Legal Control, Bike Frame, Upper Body, Lower Body, and Spokes configurations (all $p < .001$). Spokes elicited significantly shorter response times relative to each of the other five configurations (Control, Legal Control, Bike Frame, and Lower Body each $p < .001$; Upper Body $p = .002$). Surprisingly, participants responded significantly sooner to each of the Bike Frame and Upper Body conditions relative to the Lower Body option (both $p < .001$). Finally, Legal Control elicited significantly longer response times relative to Bike Frame ($p = .026$) and Upper Body ($p = .001$).

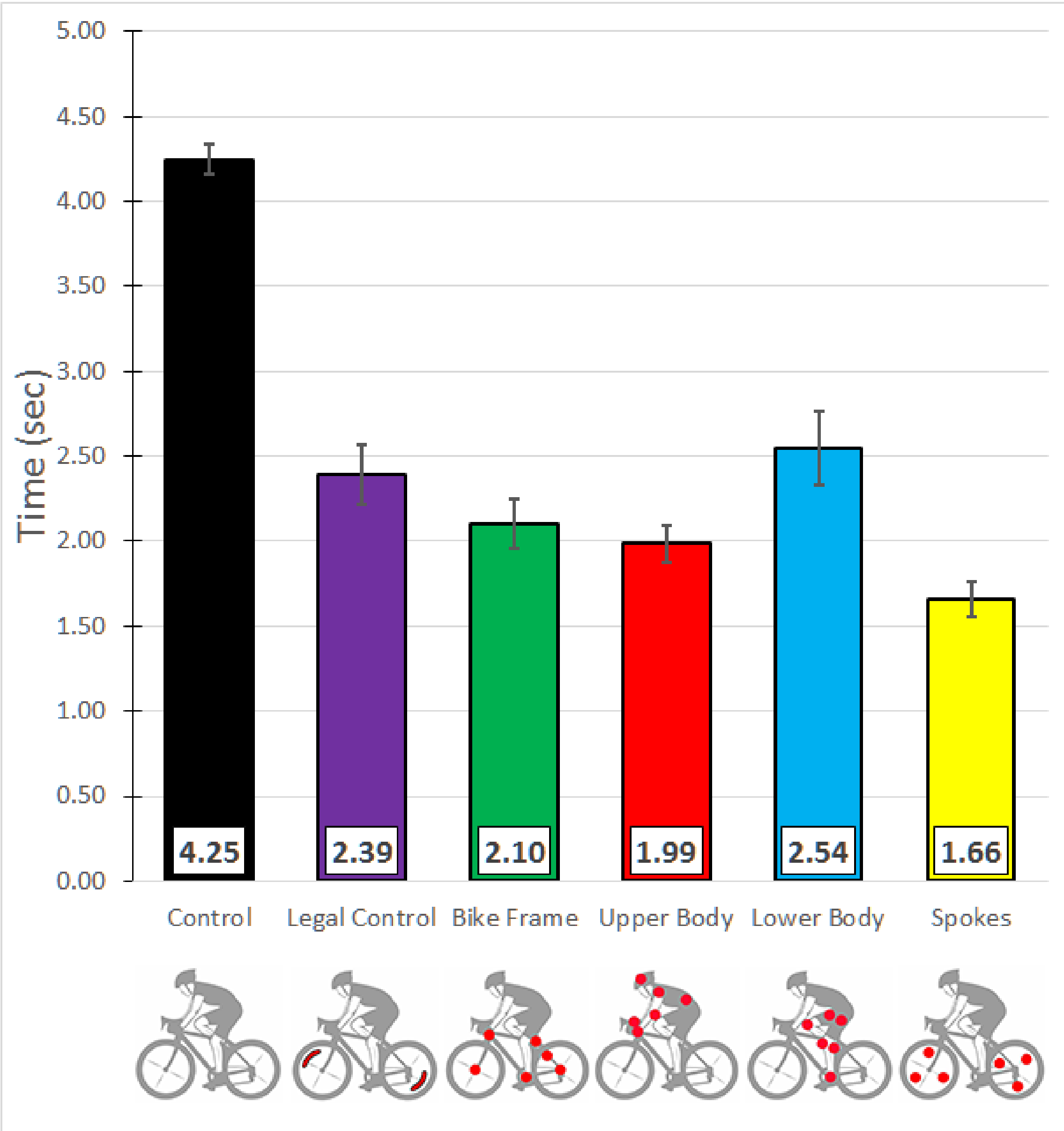


Figure 3.1 Mean response times (in seconds) as a function of the Light Placement variable. Response times for each Light Placement condition are averaged across the Pedaling/Coasting manipulation. Error bars represent ±1 standard error of the mean.

Next, Pedaling was entered into the second model. However, pedaling was not found to predict participant response times, $F(1, 484.32) = 0.077$, $p = .781$ (the mean response times were 2.33 sec for Pedaling and 2.39 sec for Coasting). The Light Placement by Pedaling interaction was then entered into the model in the third step, in order to test whether the Pedaling variable moderated the relationship between Light Placement and response times. This interaction term was found not to predict a significant portion of the variance in participant response times, $F(5, 477.95) = 0.967$, $p = 0.438$. Figure 3.2 shows participants' mean response times across the 12 combinations of the Light Placement and Pedaling variables.

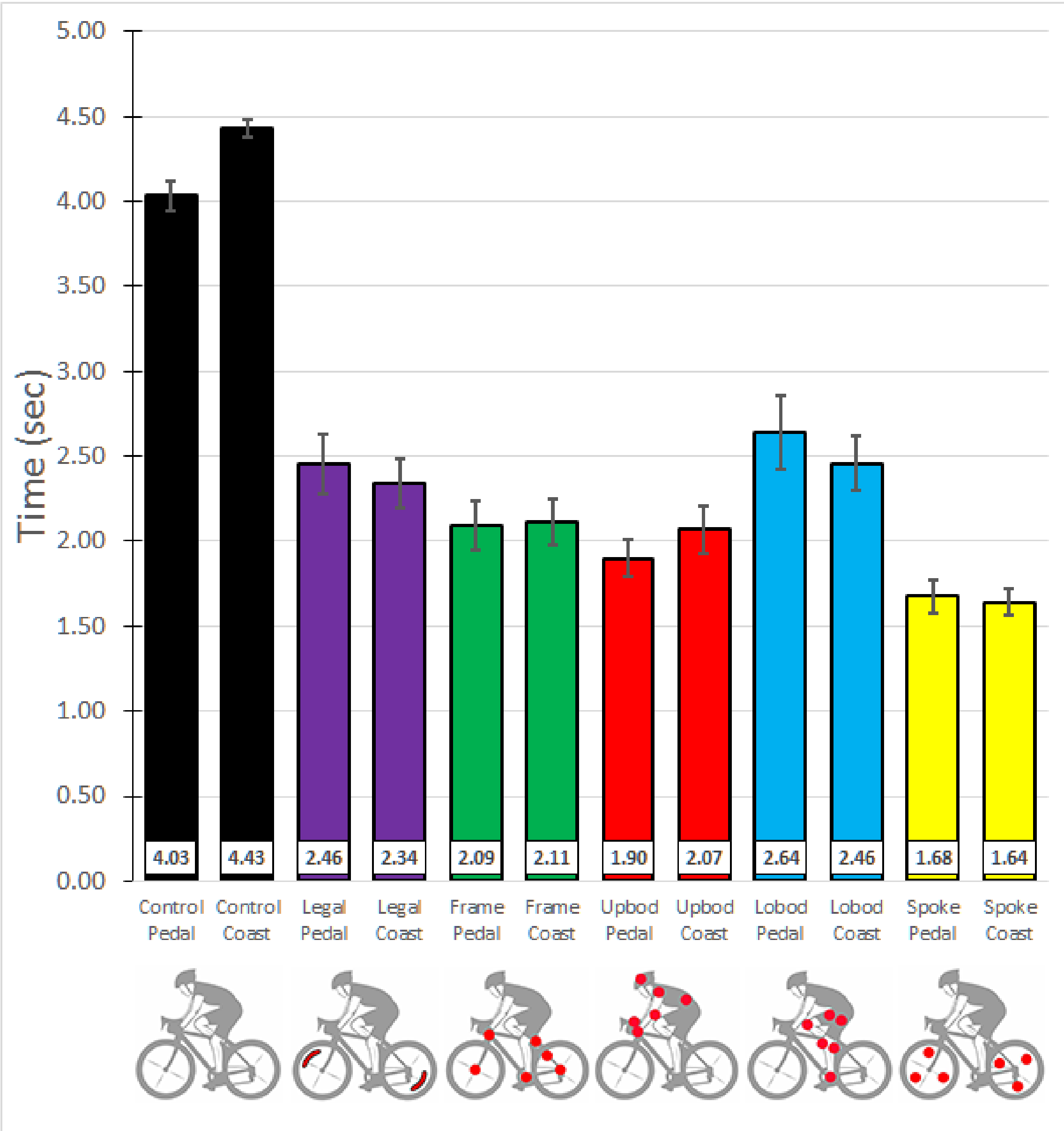


Figure 3.2 Mean response times (in seconds) as a function of Light Placement and Pedaling variables. Error bars represent ±1 standard error of the mean.

Binomial logistic regression of the probability of a missed trial

A new binary outcome variable was created from the 636 recorded bicycle trials, indexing whether a participant's response to a trial was a hit (correctly identified as a bicyclist) or a miss (misidentified). As mentioned before, the grouping of data containing misses is comprised of any trial in which a participant either failed to respond before time ran out in the trial or misidentified the hazard by pressing the incorrect button (see Appendix B). A binomial logistic regression was then conducted to analyze the predicted likelihood of participants missing a bicyclist across the experimental conditions. This was an important step because instances when a participant failed to identify a bicyclist would otherwise be unaccounted for in Experiment 1's dataset and analysis – which, as previously mentioned, was the primary reason for performing HLM instead of ANOVA. Hence there is scientific value in analyzing the likelihood of participants failing to identify a bicycle trial. This analysis regressed the probability of a missed response from three predictors: Light Placement, Pedaling, and an interaction effect between Light Placement and Pedaling. Figure 3.3 shows that the dataset of missed bicycle trials is sparsely distributed across the multiple experimental conditions, especially with there being zero misses in the Spokes condition. Though the binary logistic regression is already relatively robust to skewed datasets, an additional step was taken to address the sparseness of this dataset (Cohen, Cohen, West, & Aiken, 2003; Tabachnick & Fidell, 2007): the six levels of the Light Placement variable were collapsed and organized into three sub-groups, allowing for a greater amount of analyzable data per cell. One sub-group was comprised of participants' missed responses to the two control conditions

(Control, Legal Control). A second sub-group contained only missed responses to the ‘on-the-bicycle’ Light Placement options (Bike Frame, Spokes), and a third sub-group contained only missed responses to the ‘on-the-body’ Light Placement options (Upper Body, Lower Body).

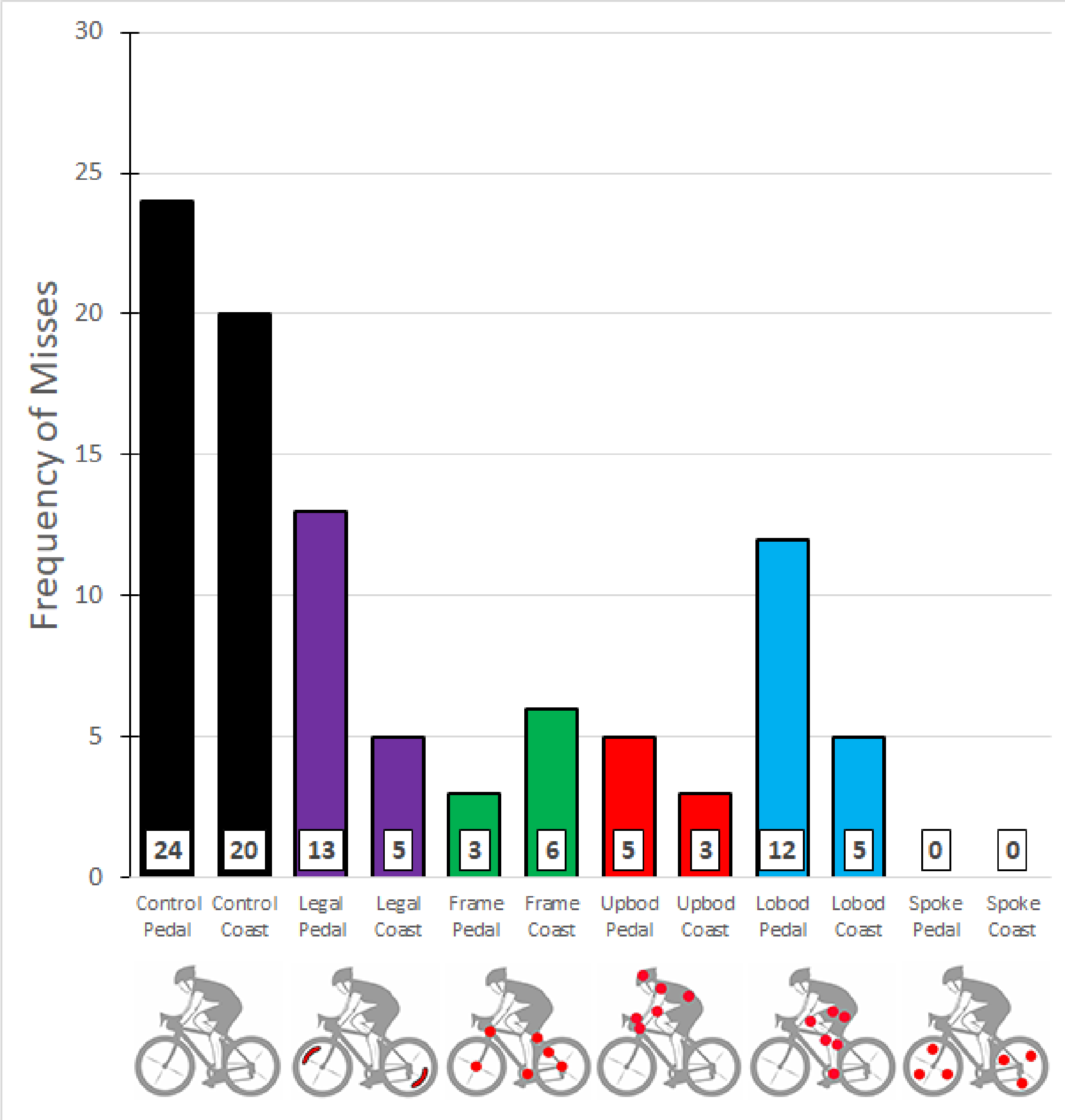


Figure 3.3 Frequency distribution of the 96 missed bicycle trials.

This model tested the main effects of each of the Light Placement and Pedaling predictors against a baseline (null) model; this strategy offers a simpler and more conservative estimate of each of their main effects relative to conducting two separate regression models of one predictor each. This model revealed that both the Light

Placement predictor [$F(4, 632) = 23.826$, $p < .001$] and the Pedaling predictor [$F(1, 632) = 4.594$, $p = .044$] accounted for a significant portion of the variance in the model relative to the null model. Further, the probability of a participant missing a bicyclist from the sub-group combining the two control conditions (29.2% misses) was significantly higher than each of the on-the-bicycle group (8.5% misses) and the on-the-body group (11.8% misses; both $p < .001$). Additionally, there was a significantly higher probability of a miss occurring within the Pedaling level (21.5% misses) compared to the Coasting level (14.7% misses) of the Pedaling variable. See Appendix E for descriptive statistics for the probability of a miss in each of the conditions in this model.

Next, the Light Placement by Pedaling interaction was included in the model to test whether the Pedaling variable moderated the relationship between Light Placement (whose levels remained organized into three sub-groups) and the probability of missing a bicycle trial. The test of this full model against the null model was found to be non-significant, $F(2, 630) = 1.850$, $p = .158$. This result indicates that there was not an interaction between the Pedaling and Light Placement variables on the probability of missing a bicyclist.

Following this, a second binomial logistic regression model was created with changes to address one potential issue from the first model. Participants in Experiment 1 successfully responded to all bicycle trials displaying the Spokes-Pedaling and Spokes-Coasting combinations (i.e., zero misses; Figure 3.3), and this could have created excessive skewness in the distribution of participants' misses. Thus, the second regression model was performed by excluding the Spokes level of the Light Placement variable (i.e., 106 trials) from analysis. In effect, this simplified the Light Placement variable to five levels and reduced the on-the-bike sub-group to include the Bike Frame configuration by itself. This version of the model failed to produce results that differed from the previous model including Spokes (see Appendix F).

CHAPTER FOUR

EXPERIMENT TWO: METHOD

Participants

Twenty-six (26) undergraduate students, who did not participate in Experiment 1, received course credit for participating in the second experiment. This sample size was determined with a power analysis, using the following estimated parameters in G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009): $\alpha = 0.05$; power $(1 - \beta) \geq 0.8$; effect size $f(V) = 1.53$. Participants in Experiment 2 met the same vision and driving experience criteria as those outlined in Experiment 1.

Design

This experiment followed a six (Light Placement) by three (Viewing Distance) within-subjects experimental design. The same six configurations of Experiment 1's Light Placement variable, seen in Table 2.1, were used in this experiment.

As in Experiment 1 the magnetic bicycle lights faced to the cyclist's left, towards a test vehicle from which participants viewed the left side of the test bicyclist. A test vehicle was parked down the road from the test bicycle at three fixed distances (50 m, 100 m, and 200 m). The presentation order of Light Placement conditions was randomized (without replacement) for each new participant appointment. For an example of the presentation orders that were used for participant appointments, see Figure 4.1.

Dist	First	Second	Third	Fourth	Fifth	Sixth
200m	CNTRL	LEGAL	UPBOD	SPOKE	LOBOD	FRAME
100m	FRAME	CNTRL	LOBOD	UPBOD	SPOKE	LEGAL
50m	LOBOD	SPOKE	LEGAL	UPBOD	FRAME	CNTRL
50m	LOBOD	CNTRL	UPBOD	SPOKE	FRAME	LEGAL
100m	FRAME	LEGAL	CNTRL	LOBOD	SPOKE	UPBOD
200m	UPBOD	CNTRL	FRAME	LOBOD	SPOKE	LEGAL
200m	FRAME	LEGAL	LOBOD	UPBOD	SPOKE	CNTRL
100m	LOBOD	FRAME	UPBOD	LEGAL	CNTRL	SPOKE
50m	LOBOD	FRAME	UPBOD	SPOKE	LEGAL	CNTRL
50m	LEGAL	LOBOD	UPBOD	FRAME	SPOKE	CNTRL
100m	UPBOD	CNTRL	LEGAL	SPOKE	LOBOD	FRAME
200m	LOBOD	LEGAL	CNTRL	UPBOD	SPOKE	FRAME
200m	LOBOD	SPOKE	LEGAL	FRAME	UPBOD	CNTRL
100m	CNTRL	LOBOD	LEGAL	UPBOD	SPOKE	FRAME
50m	LEGAL	UPBOD	LOBOD	FRAME	CNTRL	SPOKE

Figure 4.1 An excerpt of a spreadsheet used to organize the presentation order of variables to participant groups. Every three rows of data comprise one 'group' of participants in a single session. Five participant groups are shown here (i.e., each group of participants belongs to one appointment time slot, and contains up to 2 people participating at once). Each participant group saw each light configuration three times, once from each viewing distance. The abbreviations used here represent the following Light Placement levels: CNTRL = Control; LEGAL = Legal Control; LOBOD = Lower Body; FRAME = Bike Frame; UPBOD = Upper Body; SPOKE = Spokes.

Materials

The bicycle lights and apparel used in this experiment were identical to those used in Experiment 1 (see Figure 2.4).

The data collection site is a long, straight, and flat portion of a dead-end utility road on the edge of a lake (see Figure 4.2). The experimental conditions consisted of one black bicycle (Trek 7.3 FX 17.5; Model 1327010-2016) mounted to a custom stationary bicycle trainer setup (using a CycleOps Aluminum Roller and a CycleOps SuperMagneto Pro simultaneously to ensure the bicycle's stability for the rider while also ensuring both bicycle wheels rotate synchronously while pedaling) and positioned on the right side of the road's shoulder (see Figure 4.3). An experimenter acted as the test bicyclist and wore an all-black outfit (including helmet, jersey, arm covers, shorts, knee covers, socks, and shoes) for the entire duration of each experimental session. An experimenter mounted a cadence-monitoring bicycle computer (Bontrager Trip 300 and Duo Trap S) on the test bicycle to ensure the test bicyclist could maintain a 60 – 65 rpm cadence throughout data collection.

Figure 4.2 A satellite image of the service road used to collect data in Experiment 2. The red circle indicates the position of the test bicyclist at the easternmost end of the 200 m straight section. The yellow circles indicate the positions of the stationary test vehicle at the marked 50 m, 100 m, and 200 m observation points. The yellow arrows indicate participants' viewing direction (west), looking towards the stationary test bicyclist.

Figure 4.3 A magnified daytime photograph of the nighttime setup. During testing the bicyclist displayed one of the six Light Placement levels from Table 2.1. The test bicyclist wore all-black apparel (including shoes) that contained no reflective elements.

Procedure

All experimental sessions began at least one hour after sunset only on nights free from precipitation and fog, and when the road surface was completely dry. None of the data collection sessions were interrupted by inclement weather.

At the beginning of each experimental session, an experimenter met participants in the Visual Perception and Performance Laboratory. Participants then provided informed consent and demographic information, and the experimenter performed visual screening. Participants were then escorted to the test vehicle (a 2012 Subaru WRX with halogen low-beam headlamps) and were driven to the testing site. Up to two participants took part in each experimental session.

At the testing location, the experimenter explained the expectations and procedures to the participants in the vehicle. The participants did not leave the test vehicle during data collection, and the vehicle remained parked at three points along the right edge of the roadway. The participants were given a score sheet on a clipboard, pens, and a small pen-light, and were instructed (verbally and in written instructions) to respond to three prompts regarding the test bicyclist. Participants used the small pen-lights to help them complete the survey in the otherwise-unilluminated vehicle cabin. During data collection, the bicyclist pedaled at 60 – 65 rpm with both hands on the handlebars while avoiding any extraneous (non-cycling) movements.

Each of the three prompts on the score sheet asked participants to indicate the extent to which they disagree or agree with a statement about the test bicyclist in front of them (see Figure 4.4). Beneath each prompt was a horizontal line that included seven equally spaced vertical tick marks. The tick marks included text labels that ranged from "strongly disagree" to "strongly agree" used as reference points, with a neutral point in the middle. Participants were told to mark an "X" at the tick mark that represented their agreement with each prompt. After the session, an experimenter converted participants' markings to an integer between one (representing "strongly disagree") and seven (representing "strongly agree"). This method was successfully used in a similar format for past studies of judging bicyclist and road worker conspicuity (Wood, et al., 2011; Tyrrell, Fekety, & Edewaard, 2016). The ratings produced from this survey provide an operational definition of subjective bicyclist conspicuity in Experiment 2.

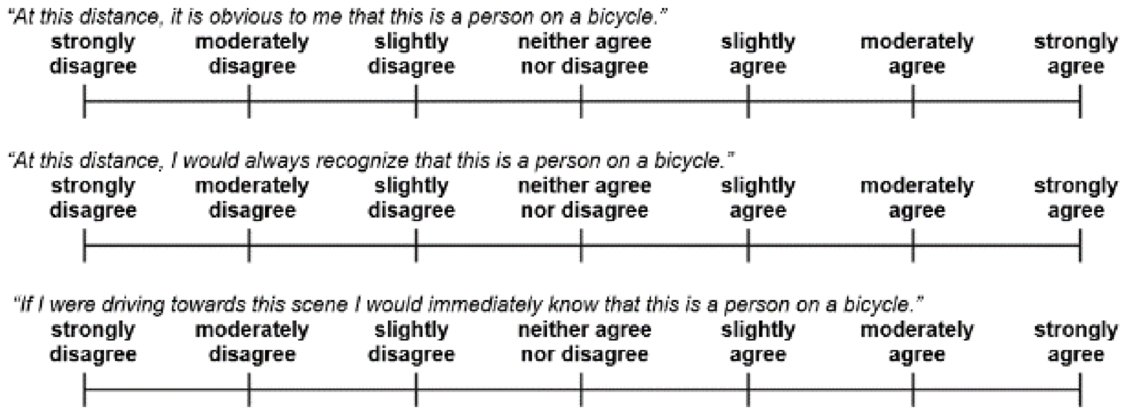


Figure 4.4 The three statements to which the participants repeatedly responded on their survey. Participants responded by marking an "X" at a point along the horizontal line corresponding to how much they agreed or disagreed with each statement. Altogether, each participant answered this group of three prompts 18 times during their session (54 ratings total).

Once all participants in the test vehicle completed ratings for each of the six Light Placement levels at one distance, the experimenter moved the test vehicle to the next viewing distance. The order in which participants experienced the levels of the Viewing Distance variable was balanced such that half of the participant appointments followed an ascending order (50 m, 100 m, 200 m) and the other half followed a descending order (200 m, 100 m, 50 m; see Figure 4.1). Each participant provided a total of 54 bicyclist conspicuity ratings during a data collection session, corresponding to the same three prompts repeated once for each of six Light Placement levels at each of three viewing distances (3 × 6 × 3 = 54). Upon completing data collection, the experimenter drove the participants back to the laboratory for debriefing and release.

CHAPTER FIVE

EXPERIMENT TWO: ANALYSIS

Twenty-six participants (*n* = 26) contributed data to this study's analysis providing a total of 1,404 conspicuity ratings across the 18 experimental conditions. A one-way repeated-measures analysis of variance (ANOVA) was conducted, using the individual survey items seen in Figure 4.4 as levels of one independent variable (e.g., a "survey item number" variable), to identify any differences in participants' response patterns among these three types of judgments they were asked to make. Mauchly's test of sphericity in this dataset indicated a violation of the sphericity assumption [χ^2 (2, N = 468) = 44.87, $p < .001$), thus Greenhouse-Geisser degrees-of-freedom corrections were used where appropriate ($\varepsilon = 0.916$). The results of this analysis revealed a significant (albeit small in magnitude) main effect of survey item number, $F(1.8, 855.5) = 34.91$, $p < 0.001$, *partial* $\eta^2 = 0.07$. Post-hoc (Bonferroni) comparisons indicated that, on average, participants' conspicuity ratings were largest for the first survey item (mean rating = 3.88), followed by the second item (mean rating = 3.64) and the third item (mean rating = 3.52) as seen in Figure 5.1.

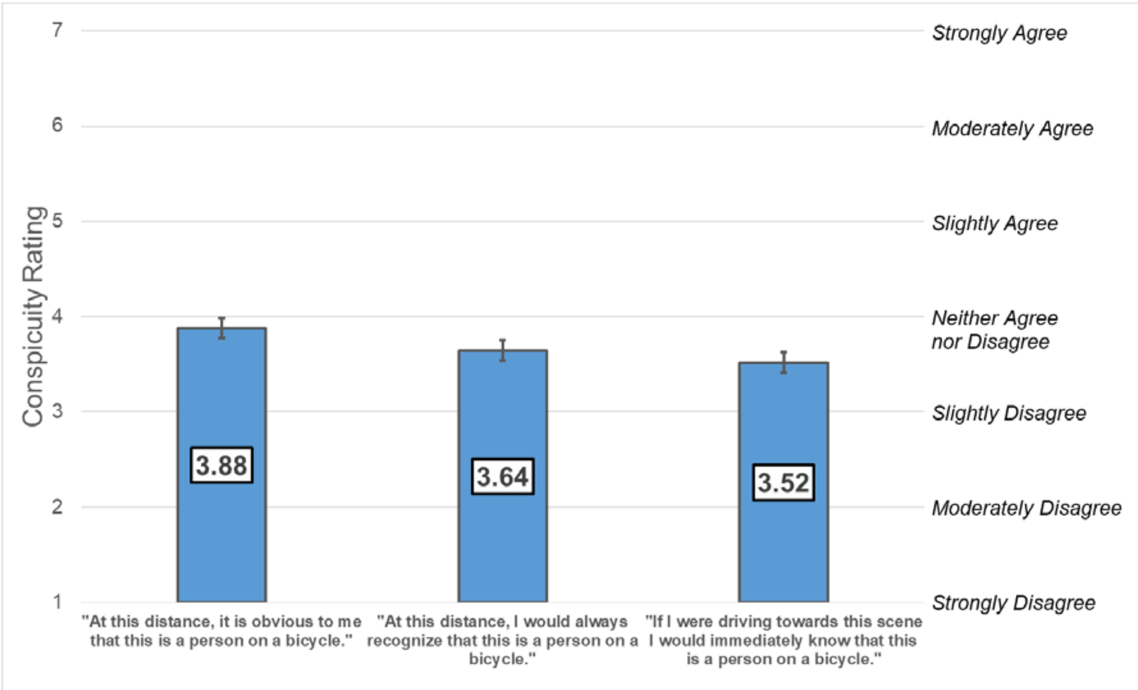


Figure 5.1 Mean conspicuity ratings as a function of the three separate survey items.

However, a follow-up reliability analysis of the data produced from these three survey items showed high reliability (Cronbach's $\alpha = 0.964$) with no indications that the reliability of the scale would improve if any of the three items were deleted (Cronbach's α if item deleted = 0.956, 0.930, and 0.954 for item 1, 2, and 3 respectively). This is not surprising, given these three survey items were designed to target redundant aspects of participants' evaluations of conspicuity. Thus, a new composite variable was created to index participants' conspicuity ratings by averaging each participant's data across the three items and this was treated as a single dependent variable.

Next, a six (Light Placement: Control, Legal Control, Upper Body, Bike Frame, Spokes, and Lower Body) by three (Viewing Distance: 50 meters, 100 meters, and 200 meters) repeated-measures analysis of covariance (ANCOVA) was conducted to quantify the separate and combined influences of the test bicyclist's lighting configurations and participants' viewing distances on conspicuity ratings. This analysis included two covariates – the identity of the experimenter acting as a test bicyclist (one of three) and the participant's seating position in the test vehicle (either the front-right seat, or the back-middle seat). Neither of these covariates explained a significant portion of the variance in the model (all $p > .05$), therefore they were eliminated from the model. Following this, a separate six by three repeated-measures ANOVA was performed with the same Light Placement and Viewing Distance variables as before. Mauchly's test of sphericity identified a violation of the sphericity assumption in each of the Light Placement [χ^2 (14, N = 26) = 32.46, $p < .05$] and the Viewing Distance [χ^2 (2, N = 26) = 23.92, $p < .001$] variables, thus Greenhouse-Geisser degrees-of-freedom corrections were used for both independent variables ($\varepsilon = 0.629$ and $\varepsilon = 0.613$ respectively). Table 5.1 and Figure 5.2 provide descriptive statistics for all manipulations and configurations in this analysis.

Table 5.1. Mean (and standard deviation) conspicuity ratings for each configuration at each of the three distances. These numbers represent a one (strongly disagree) to seven (strongly agree) scale, with four being the midpoint (neither agree nor disagree).

Viewing Distance	**Control**	**Lower Body**	**Bike Frame**	**Legal Control**	**Upper Body**	**Spokes**	**Mean**
50 m	3.61 (1.81)	5.77 (1.24)	3.54 (1.74)	5.21 (1.47)	4.46 (1.71)	5.73 (1.19)	4.72 (1.88)
100 m	1.71 (0.96)	4.79 (1.60)	2.57 (1.52)	4.56 (1.72)	3.64 (1.76)	4.32 (2.05)	3.60 (2.03)
200 m	1.41 (0.99)	3.44 (2.08)	1.83 (1.29)	3.49 (1.97)	1.73 (1.16)	4.39 (1.41)	2.72 (1.97)
Mean	2.25 (1.69)	4.67 (1.99)	2.65 (1.74)	4.42 (1.95)	3.28 (2.02)	4.82 (1.78)	3.68 (2.13)

There was a significant main effect of Distance on conspicuity ratings, $F(1.2, 30.7) = 38.34$, $p < 0.001$, *partial* $\eta^2 = 0.61$. Post-hoc (Bonferroni) comparisons indicated that cyclist conspicuity ratings significantly increased with each successive decrease in viewing distance (all $p < .001$).

There was also a significant main effect of Light Placement on conspicuity ratings, $F(3.1, 78.6) = 46.07$, $p < 0.001$, *partial* $\eta^2 = 0.65$ (see Figure 5.2). Each post-hoc (Bonferroni) pairwise comparison showed statistically significant differences among Light Placement conditions (all $p < .05$), with the exception of four non-significant findings (each $p > .05$): the Control / Bike Frame comparison, the Lower Body / Legal Control comparison, the Lower Body / Spokes comparison, and the Legal Control / Spokes comparison. When averaged across the three viewing distances participants responded to each of the Spokes, Lower Body, and Legal Control conditions with significantly higher ratings than each of the Bike Frame, Upper Body, and Control conditions. Further, participants responded to the Upper Body condition with significantly higher ratings than each of the Bike Frame and Control conditions.

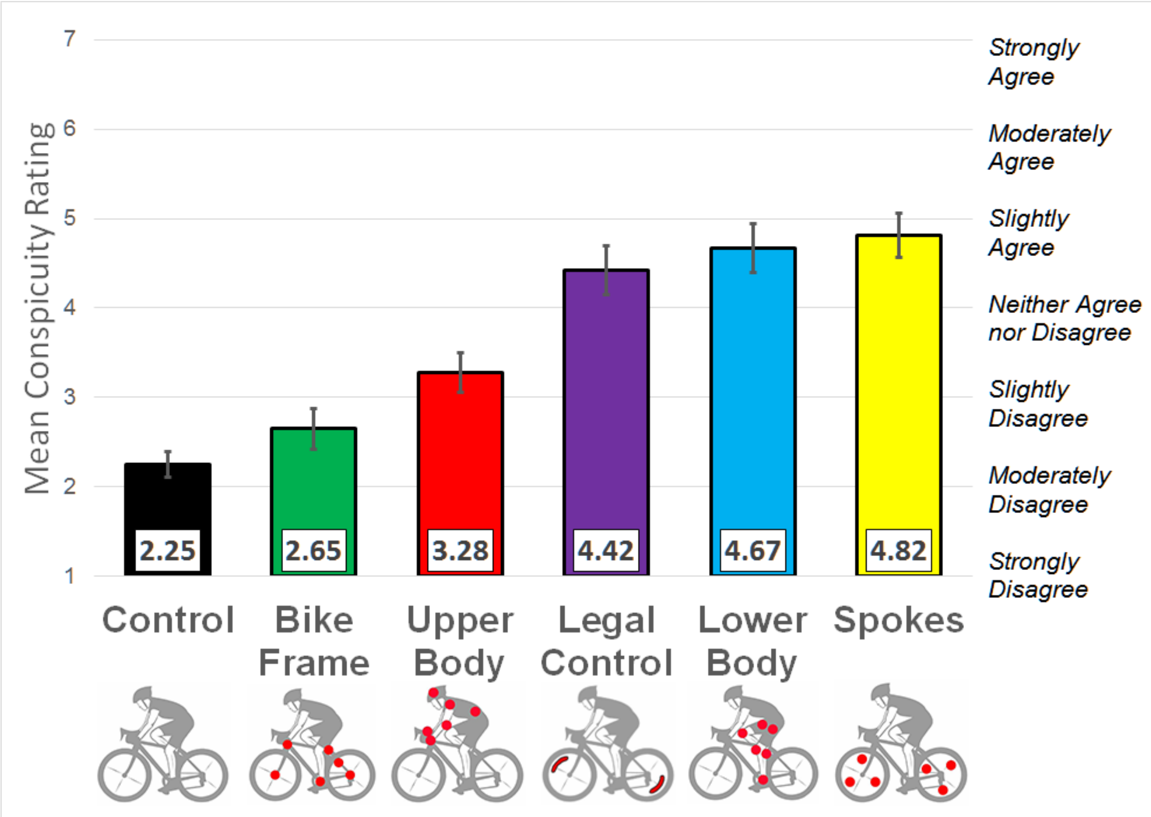


Figure 5.2 Mean conspicuity ratings of Light Placement conditions, averaged across the three Viewing Distances. Error bars represent ±1 standard error of the mean.

Most importantly, there was a statistically significant interaction between Viewing Distance and Light Placement, $F(10, 250) = 4.07$, $p < 0.001$, *partial* $\eta^2 = 0.14$ (see Figure 5.3). A Sidak-corrected simple effects test of this interaction revealed several notable patterns, which can be examined by comparing participants' conspicuity ratings of Light Placement conditions at each Viewing Distance (see Appendix G).

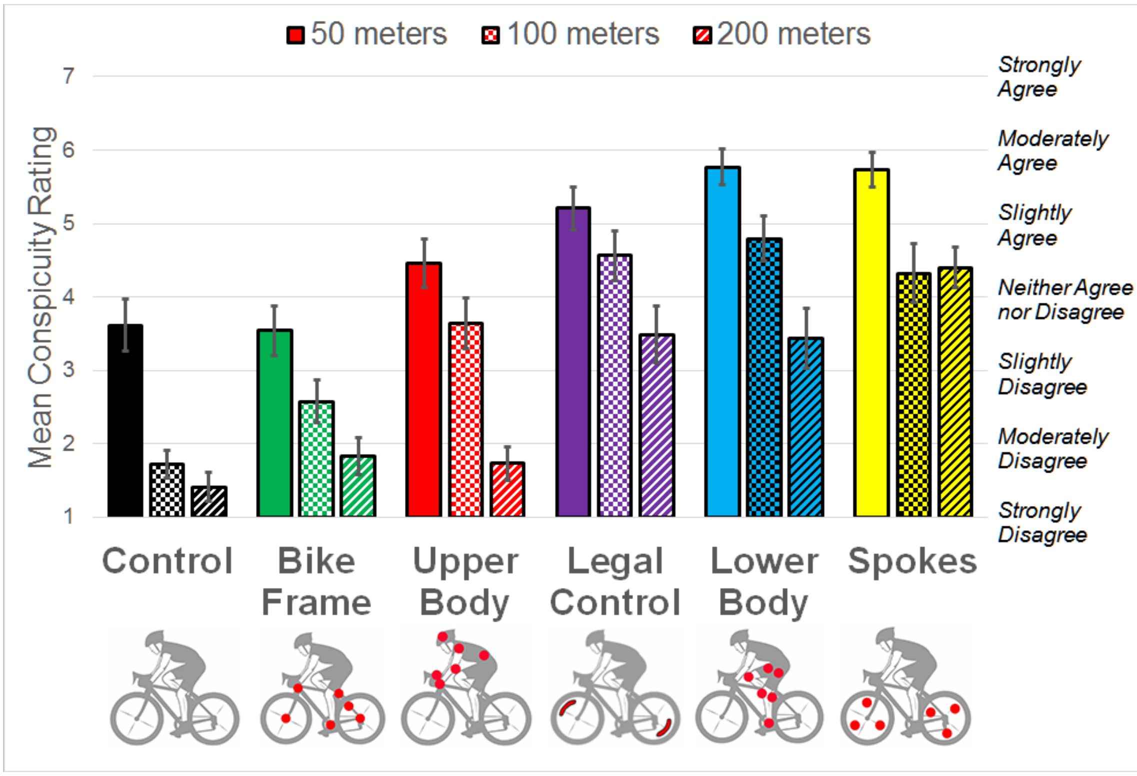


Figure 5.3 Mean conspicuity ratings as a function of Viewing Distance and Light Placement. Error bars represent ±1 standard error of the mean.

At the 200 meter and the 50 meter viewing distances, participants rated the conspicuity of the Spokes condition higher than each of the Control, Bike Frame, and Upper Body conditions separately (all $p < .05$). However, at 100 meters the Spokes condition was rated higher than only the Control and Bike Frame conditions, $p < .05$ (i.e., there were no significant differences between the Spokes and Upper Body at 100 m, $p > .05$). At all three viewing distances, the differences between the Spokes condition and the Legal Control condition were non-significant, as were the differences between the Spokes and the Lower Body condition (all $p > .05$).

A trend similar to this emerged among the ratings for the Legal Control condition at the three different viewing distances. At 200 meters, participants rated the conspicuity of the Legal Control condition higher than each of the Control, Bike Frame, and Upper Body conditions separately (all $p < .05$). However, at the 100 meter and 50 meter viewing distance, the Legal Control was rated higher than only the Control and Bike Frame conditions, $p < .05$ (i.e., the differences between the Legal Control and the Upper Body were non-significant at 100 m and 50 m, $p > .05$). At all three viewing distances, there were no significant differences between the Legal Control condition and each of the Spokes and the Lower Body conditions separately (all $p > .05$).

In contrast, the Lower Body was the only Light Placement condition to demonstrate consistency (across all three viewing distances) regarding the significant and non-significant simple effects between itself and the five other Light Placement configurations. Participants rated the conspicuity of the Lower Body condition higher than each of the Control, Bike Frame, and Upper Body conditions at 200 m, 100 m, and 50 m (all $p < .05$). In contrast, there were no statistically significant differences between the Lower Body and each of the Spokes and Legal Control conditions at 200 m, 100 m, and 50 m (all $p > .05$).

The differences observed between participants' ratings of the Control condition compared to other configurations also remained consistent across the three viewing distances, with one exception. At 200 meters and 50 meters, participants rated the conspicuity of the Control condition lower than each of the Legal Control, Lower Body, and Spokes conditions (all $p < .05$). There were also no statistically significant differences between the Control condition and each of the Bike Frame and Upper Body conditions at 200 m and 50 m. The relative differences between the Control condition and each of the Bike Frame ($p > .05$), Legal Control ($p < .001$), Lower Body ($p < .001$), and Spokes ($p < .001$) conditions were unchanged at the 100 meter viewing distance. However, participants rated the conspicuity of the Control condition significantly lower than the Upper Body condition at 100 m ($p < .001$); this particular difference was not present at 200 m or 50 m.

Participants rated the conspicuity of the Upper Body condition higher than that of the Bike Frame condition at each of the 50 meter and 100 meter viewing distances, $p < .05$. Interestingly, however, the differences between participants' ratings of these two conditions at the 200 m viewing distance were non-significant, $p > .05$.

CHAPTER SIX

GENERAL DISCUSSION

The primary purpose of these two experiments was to investigate the nighttime conspicuity benefits of bicycle lights from a side-view perspective. The secondary purpose of the study was to examine these bicycle lights' conspicuity benefits relative to the current legal bicycle reflector configuration in the United States. I hypothesized that a bicyclist's side-view conspicuity can be enhanced with the application of novel active lighting configurations that capitalize on drivers' perceptual sensitivity to motion, and that these solutions would be most effective when placed on the bicycle's rotating wheel spokes. Though I also anticipated a notable conspicuity advantage from highlighting the major joints of a rider's legs, I expected the magnitude of this effect to be less substantial than the one afforded by highlighting the bicycle's spokes. This is because, unlike lights on cyclists' legs, spoke lights highlight a dynamic movement pattern that specifies the presence of a bicyclist whether the rider is actively pedaling or not.

The findings reported here speak to the effectiveness of active lighting in a scenario inspired by an applied problem: cyclists being injured and killed in collisions with automobiles while crossing an intersection at night. In the first experiment, 53 participants watched and responded to a series of short video segments depicting 12 different combinations of a test cyclist's pedaling behavior and LED placement (or reflector placement in the case of Legal Control). In the second experiment, a separate group of 26 participants provided subjective ratings of conspicuity in response to systematic variations in the placement of bike lights (or reflectors) and viewing distance.

In total, this study collected 2,040 usable data points from participants (plus an additional 954 data points from distractor trials which were not relevant to the study's hypotheses). Taken together, these experiments measured both objective (Experiment 1) and subjective (Experiment 2) responses to the Light Placement manipulation.

In Experiment 1, when averaged across the two Pedaling levels, participants responded to the Spokes configuration earlier (that is, from a greater distance) than any other tested configuration. The response time for the Spokes configuration when averaged across Pedaling conditions (1.66 seconds elapsed since the cyclist entered the frame) was 17% earlier than that of next-best configuration (Upper Body, 1.99 sec), and 61% earlier than the Control condition (4.25 sec). To put this in perspective, a driver who is traveling 55 mph and suddenly encounters a bicyclist with the Spokes configuration would be able to begin braking or swerving from between 27 ft (Upper Body; 8 m) and 209 ft (Control; 64 m) farther, respectively. Surprisingly, the mean response time for the Lower Body configuration (2.54 sec) was 17% longer than that of the Bike Frame (2.1 sec) and 22% longer than that of the Upper Body (1.99 sec).

In Experiment 2, participants' mean conspicuity ratings formed an interesting pattern, allowing for the Light Placement levels to form two clusters. From all three viewing distances (50 m, 100 m, and 200 m), the mean conspicuity rating for each of the Spokes and Lower Body configurations were significantly and substantially greater than the Control, Upper Body, and Bike Frame configurations, with the exception of one case (see Appendix G and Figure 5.3). From the 100 meter viewing distance, there were no significant differences between participants' conspicuity ratings when pairing the Spokes and Upper Body configurations. Thus, the findings from Experiment 2, as well as the findings from related studies of the nighttime conspicuity of active bicycle lights (Edewaard, Fekety, Szubski, Tyrrell, & Rosopa, 2017), suggest that the Light Placement conditions can be grouped into two conceptually-distinct categories. Visually static configurations (e.g., Control, Bike Frame, Upper Body) are those which show minimal or no movement other than the forward (translational) progress of the bicycle/bicyclist. Visually dynamic configurations (e.g., Lower Body, Spokes) are those whose appearances continuously change (transformational and translational) as the cyclist moves and are more effective as conspicuity aids. Notably, this distinction intentionally excludes the Legal Control configuration due to its dissimilarities to other configurations which will be described in further detail below.

When examined from this perspective, the mean conspicuity rating of the static configurations decreased by 32% as participants moved from the 50 meter viewing distance to 100 meters, and decreased by another 37% from 100 meters to 200 meters. However, average conspicuity ratings of the two dynamic configurations showed a smaller decrease as participants moved farther from the test bicyclist. From the 50 meter viewing position to the 100 meter position, mean conspicuity ratings for the dynamic configurations decreased by only 21%. Participants' ratings of dynamic configurations again decreased by only 14% from the 100 meter viewing distance to the 200 meter one. Further, the mean conspicuity rating for the dynamic configurations at the 200 meter viewing distance (3.92) is 136% greater than that of the static configurations (1.66), indicating the extent to which dynamic configurations can enhance conspicuity when it matters most – long before the driver's path intersects with the bicyclist's. This large difference is present even when one excludes the Control condition from the mean static configuration rating at 200 meters: the mean dynamic configuration rating (3.92) is still 120% greater than the mean static rating combining Upper Body and Bike Frame (1.78). These findings can be interpreted in two ways. On one hand, the visually static configurations have greater potential to increase conspicuity as a driver approaches the cyclist from afar, due to the large percent-increase in mean ratings from the 200 meter to the 50 meter viewing distance. Said another way, the conspicuity benefits of the visually dynamic configurations are much more robust to increases in viewing distance relative to that of the static configurations – this is why there appears to be only a modest increase in the dynamic configurations' mean conspicuity rating from 200 meters to 50 meters.

Particularly interesting was the finding that the mean conspicuity rating for Spokes at the 200 meter viewing distance (4.39) was 13% greater than the mean conspicuity rating for the three static configurations from *50 meters* (3.87) despite the four-fold increase in observation distance. There was also no significant difference between the mean Spokes conspicuity ratings at the 200 meter viewing distance and the 100 meter position. This showed that participants' mean conspicuity ratings for the Spokes configuration at the 100 meter viewing distance were unusually small compared to the trending pattern seen within other Light Placement options at 100 meters. However, participants' ratings for the Spokes increased by 33% from the 100 meter viewing distance to the 50 meter viewing distance on average, which means that the Spokes' conspicuity remains relatively robust to increases in viewing distance. For the

Lower Body configuration, participants' mean conspicuity rating increased by an average of 39% when moving from the 200 meter viewing distance to 100 meters, and then increased by another 21% from 100 meters to 50 meters. The Lower Body was the only configuration whose mean ratings showed an incremental and significant increase from 200 meters to 100 meters to 50 meters.

Although participants' ratings of the Control configuration did not significantly differ between 200 meters and 100 meters, they did show a dramatic 111% increase from 100 meters to 50 meters on average – representing the largest percent-increase in conspicuity ratings between two adjacent viewing positions across all of Experiment 2. Mean conspicuity ratings of the Bike Frame configuration did not significantly differ between 200 meters and 100 meters, but increased by 38% from 100 meters to 50 meters, on average. The average conspicuity ratings for the Upper Body condition increased by 110% from the 200 meter viewing distance to the 100 meter viewing distance. This indicates that participants' mean conspicuity ratings were unusually high at the 100 meter viewing position relative to the trending pattern seen from other Light Placement options at 100 meters.

Among the findings from Experiment 2, another interesting trend emerged in which participants' average ratings appeared to congregate around the scale's 'Neither Agree or Disagree' region. Indeed, mean conspicuity ratings rarely exceeded the 'Slightly Agree' mark and none of the 16 Light Placement / Viewing Distance cell means reached 'Moderately Agree' (see Figure 5.3). One possible explanation is that bicyclists are, in fact, difficult to identify at night and even the most conspicuous lighting configurations from this study can improve performance in this challenging perceptual task by a modest amount. It is also possible that the intentionally strong-worded survey prompts (which included phrases like "…it is *obvious* to me…", "…I would *always* recognize…", and "…I would *immediately* know…" and specified a person on a bicycle instead of a generic roadway hazard; see Figure 4.4) contributed to participants' mostly-neutral responses. Despite this trend of neutral mean ratings, the noteworthy findings from Experiment 2 indicate that there are important differences in how sets of strategically-positioned bicycle lights convey visual information to observers and these differences can be leveraged to improve conspicuity.

The design of both experiments included two different kinds of control conditions: one 'bare-bones' condition (Control) featured black apparel and no visibility-enhancing materials. A second 'realistic' control condition (Legal Control) featured the reflectors that are legally required in the US. The former is ideal for making systematic and meaningful comparisons of the effectiveness of the active lighting solutions. The latter was the only configuration to make use of passive reflectors, and a critical point must be made about interpreting comparisons between the Legal Control condition and the active lighting configurations. The findings related to the study's Legal Control configuration are of secondary importance in the context of this project because it is fundamentally different from the active lighting configurations. The inclusion of the Legal Control condition in this study represents a typical approach to enhancing side-view conspicuity and a practical reference point from which to consider the findings of the novel active lighting configurations. This condition should not be considered a fair comparison against any of the other experimental configurations. In contrast, the baseline Control condition features a cyclist in black clothing without any reflectors or lights present. The all-black Control condition's inclusion in this study was crucial for maintaining experimental control, i.e., inferring the effectiveness of the active lighting configurations via comparison to a baseline condition.

It is also notable that the Legal Control condition and the Spokes condition, when viewed perpendicularly, each highlight wheel rotation. Despite this, it is decidedly not the purpose of this study to directly compare the effectiveness of passive reflectors and active lighting as conspicuity-enhancing materials/solutions. In other words, this research should not be seen as a comparison of the relative benefits of active lighting and passive reflectors. This is the case for several reasons. First, the prismatic reflectors used in the Legal Control condition were iteratively designed specifically for the purpose of improving the side-view conspicuity of bicyclists at night. Their material construction, reflective qualities, physical dimensions and positioning have all resulted from industry and government efforts to address the specific problem of the side-view conspicuity of bicyclists at night. In contrary, the LEDs used in this study were not designed with this application in mind. Second, the passive retroreflectors and the LEDs have critical differences in how they transmit light to approaching drivers. Past research (Fekety, Edewaard, Stafford Sewall, & Tyrrell, 2016) has confirmed that the benefits of retroreflectors are dependent on the presence and aiming of an approaching vehicle's headlight beam in order to be effective, and that retroreflective elements are insufficiently conspicuous to drivers when they are positioned outside of this headlight beam (e.g., just before a vulnerable road user crosses the street in front of an approaching car). Thus a vulnerable road user adorned with reflectors becomes less visible as they move farther away from an approaching vehicle's headlights. Said another way, the reflectors are not maximally visible until the bicyclist is positioned directly in front of the approaching test vehicle. This is counter-productive to the goal of ensuring vulnerable road users are visible and identifiable to drivers long before a potential crash. Thus, there is a discrepancy between the appearance of this study's LEDs (which emit a consistent luminance) and the reflectors in the Legal Control configuration. Third, the set of six LEDs from the active lighting conditions collectively display only 42 mm^2 of surface area, which is less than 1% of the surface area of the reflectors (which totaled 4,840 mm^2). The reflectors are much larger in physical dimensions, but their sensitivity to changes in illumination and roadway geometry (as previously mentioned) counteract their larger size. Taken together, the differences between the LEDs in the active lighting configurations are sufficiently different from the reflectors used in the Legal Control condition that it makes it difficult to use the present data to make meaningful comparison of the conspicuity-enhancing potential of the two types of materials/solutions used in this project.

With all of this in mind, it is perhaps best to discuss participants' responses to the Legal Control configuration separately from those of the active lighting configurations. In Experiment 1, the mean response time for the Legal Control configuration (2.39 sec) was 44% shorter than that of the baseline Control configuration (4.25 sec). However, participants' Bike Frame (2.10 sec) and Upper Body (1.99 sec) response times were found to be 12% shorter and 17% shorter than that of the Legal Control configuration, respectively. As a reminder, the Upper Body and Bike Frame configurations are modest applications of active lighting on a rider's body or bicycle, whose arrangements are typically unmoving and are not optimally configured to facilitate the perception of a bicyclist crossing the street. Despite this, the findings indicate that these configurations can offer a quantifiable conspicuity advantage over the current legal bicycle reflectors in the United States. In Experiment 2, participants' mean ratings of the Legal Control condition did not significantly differ between the 50 meter viewing distance and the 100 meter position. However, mean participant ratings showed a 24% decline on average from the 100 meter viewing distance to the 200 meter position, as well as a 33% decline from the 50 meter position to the 200 meter position. This suggests that the reflectors of the Legal Control configuration can be effective conspicuity aids when observers are positioned close to the bicyclist, but their effectiveness in facilitating the perception of a bicyclist decreases with greater viewing distances. Importantly though, the most effective conspicuity aids are those which indicate the presence of a bicyclist to a driver who is far enough away to begin an avoidance maneuver; a distance of 50 or 100 meters separating a bicyclist from an approaching car is likely not enough for this to be the case.

Literature from the perceptual sciences indicates that stimuli that are highly salient are typically more conspicuous and attention-grabbing than less salient (i.e., static or unchanging) stimuli (Yantis & Jonides, 1984; Theeuwes, 1992), and that humans possess a strong perceptual sensitivity to biological motion stimuli in particular (Blake & Shiffrar, 2007; Johansson, 1973). In fact, these findings formed the basis for the current study's hypotheses. However, the current study's findings indicate that, for a bicyclist crossing in front of a vehicle while illuminated only by the approaching vehicle's headlamps, a set of LEDs positioned on the bicycle's spokes can be just as (if not more) conspicuous than LED configurations highlighting the rider's pedaling legs. Indeed, the mechanical motion of a bicycle's rotating wheels is one of the most visually dynamic and recognizable movement patterns featured anywhere on a bicycle or its rider. Therefore, although humans could not have evolved a perceptual sensitivity to recognizing rotating bicycle wheels, this study's findings suggest that the image of a pair of spinning wheels positioned adjacent to each other with a fixed separation is a powerful stimulus that clearly facilitates the perception of a bicyclist. Thus, when viewed from the side, the mechanical dynamics of rotating bicycle wheels conveys rich visual information whose conspicuity benefits are roughly similar to that of a bicyclist's legs' rhythmic pedaling motion. As stated earlier, a key advantage of highlighting the rotating wheels is that the wheels continue to rotate even when the bicyclist is coasting.

There is also an interesting question, pertaining to the appearance of spoke lights, which could be examined through future research. The Spokes configuration featured three small, white LEDs positioned on the spokes of each wheel. Each light was positioned on the spoke at approximately three-quarters of the way between the center axle and the wheel rim; lights on each wheel were spaced equidistant from each other and formed an equilateral triangle. This light configuration created the perception of three individual points of light moving counter-clockwise in a circle when the test bicyclist was crossing the street. However, this is only one of many possible ways for spoke lights to be configured on a bicycle. Simple adjustments to the positioning of the lights on a wheel (e.g., lights placed closer or farther away from the center axle, or uneven spacing between the three lights) would produce a different perceptual experience for an approaching driver who is viewing their pattern of rotational movement. For example, three spoke lights positioned near the axle of the wheel would resemble a smaller, 'uninterrupted circle' of light rather than three individual rotating points of light (assuming travel speed is identical to that of the present study). As discussed previously, the pattern of visual information conveyed by a continuous circle of light on spinning bicycle wheels appears less dynamic than a pattern in which individual points of light on the wheels can be seen rotating around the center axle while the bicycle is in motion. Additionally, factors such as a cyclist's travling speed and the number of lights affixed to each wheel have a notable impact on the dynamic appearance of rotating spoke lights. A greater number of spoke lights positioned on each wheel means that the cut-off point between the perception of individually rotating lights and an uninterrupted circle of light occurs at lower bicycle traveling speeds. Similarly, a bicyclist crossing the street at a faster traveling speed would need fewer lights on each wheel in order to preserve the approaching driver's perceptual experience of individually rotating lights. This is because adding larger quantities of lights to the wheel in a circular shape means that there is less physical space separating each LED, and when the wheel rotates at speed observers will perceive the light from each spoke 'blend' together to form the appearance of a single circle of light. Therefore, maximally dynamic spoke lights should be configured in such a way that they are positioned far away from the center axle of the wheel, and the number of lights used is small enough that observers can easily perceive the individual pattern of motion of each light when the wheel rotates.

Although this study found a significant conspicuity advantage from positioning active lighting on a bicyclist's legs, the magnitude of this effect was less than expected. Participants' response times to the Lower Body configuration were longer than that of any other Light Placement option (excluding Control). Further, there was a higher likelihood of participants in Experiment 1 failing to respond to the pedaling Lower Body configuration than any of the five other (non-control) combinations of Light Placement and Pedaling levels. It is worth noting that a bicycle's pedals and crank arm are designed to produce very specific movement patterns and typically do not afford natural ("biological") movement when a rider interacts with them. The fact that a rider's leg movements are constrained by the bicycle's mechanical components means that this study's observers were presented with 'degraded' biological motion, and this may have negatively impacted conspicuity. In other words, the motions that a rider's legs make while on a bicycle are dissimilar from a natural walking or running motion and this may make it more difficult for approaching drivers to recognize a crossing cyclist solely by the motion of their pedaling legs. While it seems possible that highlighting both a rider's leg movements *and* the bicycle's wheels would result in conspicuity being higher yet, that configuration was not included in either of these experiments. Future testing would be necessary to explore the conspicuity benefits of highlighting both leg movements and wheel rotation.

This project also revealed an instance when people's real-world subjective judgments of conspicuity are inconsistent with their objective responses. Participants' survey responses from Experiment 2 demonstrated that the subjective conspicuity of the Lower Body configuration was among the best, and on par with that of the Spokes and Legal Control – two visually similar configurations which are designed to elicit strong perceptions of motion. However, participants' responses to the video stimuli in Experiment 1 indicate that the pedaling Lower Body configuration was one of the least identifiable active lighting configurations. Together, these findings suggest a few possible explanations. For example, the conspicuity advantages of the Lower Body's pedaling motions could appear more impressive when the rider is pedaling on a stationary bicycle – which was the setup used in the current study's Experiment 2 as well as Wood, et al. (2012) and Stapleton and Koo (2017) – than when the cyclist is riding normally. That is, the pedaling movements may be particularly useful in the absence of forward translation of the bicyclist. Alternatively, the dynamic appearance of the pedaling Lower Body configuration may have been insufficiently captured in the video format used in Experiment 1 and this discrepancy may have contributed to participants' poorer performance with this condition. Additional testing would be necessary to distinguish between these possibilities.

It is important to re-examine this study's findings in the context of the existing literature. One study of cyclists' nighttime conspicuity (Costa, et al., 2017) showed that cyclists who cover the length of their bicycle's crank arm with reflective tape can increase the distance from which a driver approaching from behind can recognize them by almost twofold relative to a control (i.e., no lights or reflectors). Interestingly, these authors also reported a lack of an effect on recognition distances when adding retroreflective tape to the bicycle frame (specifically around the seat post, left and right seat stay tubes, and the back of a rigid carrier rack) relative to a control condition. Despite the fact that the Costa, et al. study focused on conspicuity of a cyclist when viewed from behind, and the authors chose to configure their test bicycles with retroreflective tape instead of active light sources, both their study and the current one indicate that highlighting the motion of mechanical bicycle components can be a beneficial strategy toward improving cyclists' nighttime roadway safety.

Past work conducted on a closed-road circuit in Australia (Wood, et al., 2013) indicated that people who identified as occasional and frequent cyclists overestimated their own conspicuity – in terms of the distance at which they judged an approaching driver would just recognize them as a cyclist, compared to the actual recognition distances collected from the approaching drivers. Interestingly, the judgments made by these cyclists indicated a failure to understand or appreciate the conspicuity advantages of positioning retroreflective markings on a cyclist's ankles and knees. These findings somewhat contradict those reported in the present study, which suggest that observers (who were not necessarily active cyclists themselves) overestimated the conspicuity of highlighting the motion of a rider's pedaling legs in Experiment 2 relative to the poor response times collected for the same configuration in Experiment 1. However, it is worth noting that the experimenters in the Wood, et al. study asked participants to make their judgments of conspicuity while they pedaled the test bicycle, rather than sitting in the approaching vehicle. This point may account for the discrepancies in results between the present study and the Wood, et al. (2013) study.

Another study of nighttime bicyclist conspicuity, published by Stapleton and Koo (2017), collected eye-tracking data from participants who observed videos depicting a driver approaching a cyclist from behind at night. The authors' primary manipulation in this study involved four different configurations of retroreflective markings on their test bicyclist's black apparel: a biomotion condition highlighting the rider's knees and ankles, a 'pseudo-biomotion' retroreflective strip on the rider's calves which formed a line connecting the back of their knees and ankles, a retroreflective vest configuration, and control. Interestingly, the authors found evidence favoring the conspicuity advantages of the biomotion configuration, in the form of quantitative gaze data (i.e., saccades and fixations) and participants' qualitative post-test survey responses. These results on rear-view cyclist conspicuity, in conjuction with similar findings published by the same research lab (Koo & Huang, 2015; Koo & Dunne, 2012) and the findings related to side-view conspicuity in the present study, indicate that highlighting a cyclist's pedaling legs with high-visibility materials can offer profound conspicuity advantages at night. It is noteworthy, however, that differences in cyclist orientation (rear and side view) and the high visibility materials chosen (retroreflectors and active lights) means that the cyclists would appear much different between the Stapleton and Koo study and the present work. Further, it remains to be seen precisely how the effectiveness of highly dynamic conspicuity solutions, like the present study's Spokes condition for example, would differ between a side view and a rear view. With this in mind, it is important for future research to address the need for nighttime cyclists to be conspicuous to drivers with consideration for many viewing angles, viewing distances, and rider and driver behaviors.

Importantly, there are a number of factors limiting the practical application of this study's active lighting solutions to improve cyclists' nighttime roadway safety. First and foremost, these light products were designed to be visible at night when there is little ambient illumination in the roadway environment. Although their daytime use was not formally tested in this study, LEDs featuring 15,000 mcd and a 3 mm diameter will not be visible to drivers from relevant distances in daylight. This is not a design flaw of the LEDs, since the manufacturers designed the LEDs for nighttime use. However, it implies that it is the responsibility of both light manufacturers and bicycle riders to understand and appreciate that not all active lighting solutions share the same advantages (or even the same applications), and to ensure their chosen active lighting solutions are used in the appropriate settings.

Additionally, the LEDs used in this project draw power from disposable lithium-ion 'coin' batteries. Thus, these specific lights' effectiveness as conspicuity aids is entirely dependent upon a) the rider remembering to turn the lights on before riding, and b) the batteries being charged. Further, if the batteries used in this study's lights were to run out of charge part-way through a ride, it would be difficult to carefully disassemble the lights and replace the batteries outside at night. Despite all of this information, the purpose of the present study was not to evaluate this specific LED product for use in this application. Instead, this project evaluated possible conspicuity solutions by examining the perceptual information most beneficial to drivers. In other words, the appearance and configuration of active lights in this study is far more scientifically valuable than the specific type or brand of light that was selected, and any potential shortcomings of the design of the LED products themselves do not diminish the value of the study's findings. Rather, this study offers valuable insights related to the optimal configuration and usage of lights, which can then be used to drive industry design decisions for bicycle lights in the future.

There is also an issue pertaining to the proper aiming and alignment of the beam of light emitted from the LED casing relative to the eye of an observer or approaching driver; this applies to all active lighting solutions, not just this project's LEDs. Although the LEDs used in the current study disperse a relatively wide cone of light, so as to be visible from a range of observation angles, they were designed to be maximally conspicuous when viewed head-on. Regarding the design and usage of active lights, it is likely that there will always be a trade-off between luminous output and the spread of a light's beam; greater luminance aimed in one direction means poorer visibility in other directions, and vice versa. This means that this project's LED configurations (like the majority of others) are conspicuous when an observer views them on a bicyclist at a perpendicular angle, but their conspicuity when viewed off-axis (i.e., from behind or in front of the rider) remains untested. For example, it is likely that the visibility of the Spoke lights would be greatly diminished when viewed from the front or rear of the bicycle, due to the fact that Spoke lights cannot be optimally aimed for forward or rear visibility. Fortunately, research has shown that lights on a rider's legs can be configured to improve rear conspicuity when appropriately aimed (Edewaard, Fekety, Szubski, Tyrrell, & Rosopa, 2017; Tyrrell, Fekety, & Edewaard, 2016). All of these points discussed here will necessarily impact the nighttime conspicuity of riders who choose to use active lighting solutions. Therefore it is important to remember that the legally-mandated prismatic reflectors used in the Legal Control condition are still useful conspicuity solutions, as they do not require the user to turn them on before riding, nor do they need a power source to reflect light.

In closing, this study was the first of its kind to examine the nighttime conspicuity benefits of a different configurations of active lights on a bicyclist viewed from the side. The two experiments designed for this study measured both participants' subjective judgments of, and objective performance to, different LED configurations on the bicyclist's body and bicycle. The converging findings from this study reinforce the idea that highlighting the dynamic, rotating mechanical motion of a bicycle's wheels is a particularly powerful tool to enhance the nighttime conspicuity of riders when viewed from the side. This is due in part to the fact that spoke lights retain their dynamic appearance regardless of whether the cyclist is pedaling or coasting. Additionally, this study contributes to a growing body of evidence in the literature that specifies highlighting the biological motion of a pedaling rider's legs can enhance conspicuity relative to the less-effective strategy of highlighting the unmoving joints of the body. It is hoped that eventually these results will further inspire industry designs and government regulation of new conspicuity-enhancing solutions for nighttime bicyclists.

APPENDICES

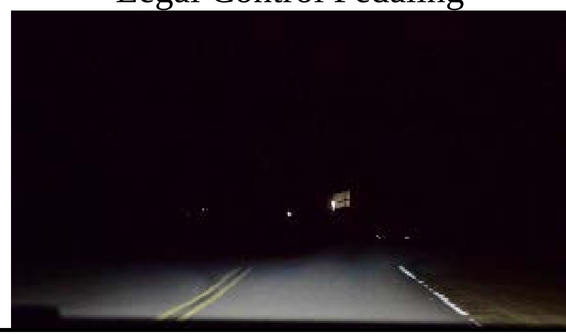
Appendix A
Selected Screenshots from Experiment 1 Video Stimuli

Car oncoming

Bike Frame Coasting

Group of joggers crossing

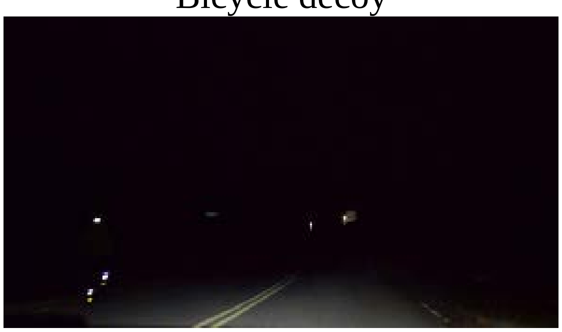
Legal Control Pedaling



Light post (left)

Lower Body Pedaling

Bicycle decoy



Spokes Pedaling

Appendix B
Experiment 1 Frequency of Hits and Misses by Condition

Table B1 Frequency and percentage statistics for participants' hits and misses in data collection trials.

	No response	**Misidentification**	**Total Misses**
Control Pedaling	12	12	24
Control Coasting	11	9	20
Legal Control Pedaling	4	9	13
Legal Control Coasting	1	4	5
Bike Frame Pedaling	0	3	3
Bike Frame Coasting	0	6	6
Upper Body Pedaling	0	5	5
Upper Body Coasting	0	3	3
Lower Body Pedaling	0	12	12
Lower Body Coasting	0	5	5
Spokes Pedaling	0	0	0
Spokes Coasting	0	0	0
Total	28 (29.2%)	68 (70.8%)	96 (100%)

Participants' incorrect responses were categorized as either a failure to respond or a misidentification of the hazard. For example, a participant could watch a video trial from start to finish and be unable to perceive any road users or hazards despite the fact that there was at least one (no response). By another example, a participant could watch a video trial containing a bicyclist; the participant could then mistakenly perceive the bicyclist as a jogger and press the key to signify a pedestrian (misidentification). Collectively, both of these events are classified as misses for this analysis.

Appendix C

Descriptive Statistics for each Binomial Logistic Regression Model in Experiment 1

Descriptive Statistics: Null Model (Logit)

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Null_logit	530	-2.22	-.37	-1.5997	.53894	.290
Valid N (listwise)	530					

Descriptive Statistics: Light Placement Main Effect Model (Logit)

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
NewLights_logit	636	-4.02	.44	-2.1371	1.13869	1.297
Valid N (listwise)	636					

Descriptive Statistics: Pedaling Main Effects Model (Logit)

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
Pedaling_logit	530	-2.50	-.13	-1.6204	.60117	.361
Valid N (listwise)	530					

Descriptive Statistics: Light Placement and Pedaling Main Effects Model (Logit)

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
MainE_logit	530	-3.89	1.52	-1.8790	1.14907	1.320
Valid N (listwise)	530					

Descriptive Statistics: Light Placement * Pedaling Interaction Model (Logit)

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
INT_logit	530	-3.93	1.46	-1.9228	1.21476	1.476
Valid N (listwise)	530					

<u>Appendix D</u>
<u>Experiment 1 Hierarchical Linear Model Outputs</u>

Table D1. HLM containing Light Placement and Pedaling main effects, plus the interaction effect.

	Model 1		**Model 2**		**Model 3**		**Model 4**	
effect	***Estimate***	***(Standard Error)***	***Estimate***	***(Standard Error)***	***Estimate***	***(Standard Error)***	***Estimate***	***(Standard Error)***
intercept	2.358633	0.074646	4.290081	0.122683	4.298797	0.126724	4.425172	0.155670
Level 1 Light Placement			-1.899037	0.133424	-1.899142	0.133555	-2.096310	0.182143
Level 1 Pedaling					-0.019217	0.069219	-0.288393	0.205695
Level 1 Lights * Pedaling							0.421165	0.267855
Change in Model R2			**0.485803013**		**---**		**---**	
	Resid = 1.234276		**Resid = 0.634661**		**Resid = 0.635899**		**Resid = 0.636548**	

The model with the Light Placement main effect reduced the residual variance by 49% relative to the baseline model. Numbers highlighted in yellow indicate significant effects.

Appendix E
Descriptive Statistics for Experiment 1 Probabilities of Missed Trials

Descriptive Statistics: Predicted Probability for a Missed Trial Across Light Placement Levels

with spokes		N	Minimum	Maximum	Mean	Std. Deviation	Variance
Bike Lights	Predicted Probability for miss = 1.000	106	.023	.325	.08491	.066908	.004
	Valid N (listwise)	106					
Body Lights	Predicted Probability for miss = 1.000	212	.020	.511	.11792	.097697	.010
	Valid N (listwise)	212					
Control Groups	Predicted Probability for miss = 1.000	212	.052	.820	.29245	.190794	.036
	Valid N (listwise)	212					

Descriptive Statistics: Predicted Probability for a Missed Trial Across Pedaling Levels

Pedaling		N	Minimum	Maximum	Mean	Std. Deviation	Variance
Pedaling	Predicted Probability for miss = 1.000	265	.035	.820	.21509	.179717	.032
	Valid N (listwise)	265					
Coasting	Predicted Probability for miss = 1.000	265	.020	.722	.14717	.144107	.021
	Valid N (listwise)	265					

Appendix F
Experiment 1 Binomial Logistic Regression F-tables

Light Placement predictor (with Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	23.629	2	633	.000
NewLights	23.629	2	633	.000

Probability distribution:Binomial
Link function:Logit

Light Placement predictor (without Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	14.768	2	527	.000
NewLights2	14.768	2	527	.000

Probability distribution:Binomial
Link function:Logit

Pedaling predictor (with Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	4.083	1	634	.044
pedaling	4.083	1	634	.044

Probability distribution:Binomial
Link function:Logit

Pedaling predictor (without Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	4.294	1	528	.039
pedaling	4.294	1	528	.039

Probability distribution:Binomial
Link function:Logit

Light Placement * Pedaling interaction (with Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	10.541	5	630	.000
NewLights	22.986	2	630	.000
pedaling	0.677	1	630	.411
NewLights*pedaling	1.850	2	630	.158

Probability distribution:Binomial
Link function:Logit

Light Placement * Pedaling interaction (without Spokes)

Fixed Effects

Target:Miss or Hit
Reference Category:correct

Source	F	df1	df2	Sig.
Corrected Model ▼	7.085	5	524	.000
NewLights2	14.735	2	524	.000
pedaling	0.578	1	524	.447
NewLights2*pedaling	1.876	2	524	.154

Probability distribution:Binomial
Link function:Logit

Appendix G
Experiment 2 Simple Effects Test of the Light Placement & Pedaling Interaction

Pairwise Comparisons

Measure: Conspicuity Rating

Viewing Distance	(I) Light Placement	(J) Light Placement	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
50 meters	Control	Lower Body	-2.154*	.330	.000	-3.221	-1.087
		Bike Frame	.077	.321	1.000	-.963	1.117
		Legal Control	-1.590*	.394	.007	-2.863	-.316
		Upper Body	-.846	.276	.075	-1.740	.047
		Spokes	-2.115*	.342	.000	-3.221	-1.009
	Lower Body	Bike Frame	2.231*	.300	.000	1.261	3.200
		Legal Control	.564	.297	.661	-.398	1.526
		Upper Body	1.308*	.340	.011	.207	2.409
		Spokes	.038	.179	1.000	-.539	.616
	Bike Frame	Legal Control	-1.667*	.417	.007	-3.015	-.319
		Upper Body	-.923*	.257	.021	-1.755	-.092
		Spokes	-2.192*	.288	.000	-3.125	-1.260
	Legal Control	Upper Body	.744	.360	.531	-.420	1.907
		Spokes	-.526	.287	.707	-1.453	.401
	Upper Body	Spokes	-1.269*	.343	.016	-2.379	-.160
100 meters	Control	Lower Body	-3.077*	.319	.000	-4.110	-2.044
		Bike Frame	-.859	.298	.114	-1.824	.106
		Legal Control	-2.846*	.279	.000	-3.750	-1.943
		Upper Body	-1.923*	.330	.000	-2.992	-.854
		Spokes	-2.603*	.349	.000	-3.731	-1.474
	Lower Body	Bike Frame	2.218*	.330	.000	1.152	3.284
		Legal Control	.231	.399	1.000	-1.060	1.522
		Upper Body	1.154*	.295	.009	.200	2.107
		Spokes	.474	.470	.997	-1.047	1.996
	Bike Frame	Legal Control	-1.987*	.426	.001	-3.365	-.610
		Upper Body	-1.064*	.279	.012	-1.967	-.161
		Spokes	-1.744*	.443	.009	-3.176	-.312
	Legal Control	Upper Body	.923	.451	.546	-.535	2.381
		Spokes	.244	.283	1.000	-.672	1.160
	Upper Body	Spokes	-.679	.491	.948	-2.268	.909
200 meters	Control	Lower Body	-2.026*	.358	.000	-3.182	-.869
		Bike Frame	-.423	.234	.727	-1.181	.335
		Legal Control	-2.077*	.330	.000	-3.146	-1.008
		Upper Body	-.321	.210	.894	-.998	.357
		Spokes	-2.987*	.230	.000	-3.731	-2.244
	Lower Body	Bike Frame	1.603*	.282	.000	.690	2.516
		Legal Control	-.051	.279	1.000	-.954	.851
		Upper Body	1.705*	.292	.000	.761	2.649
		Spokes	-.962	.341	.129	-2.063	.140
	Bike Frame	Legal Control	-1.654*	.328	.001	-2.716	-.592
		Upper Body	.103	.166	1.000	-.435	.640
		Spokes	-2.564*	.235	.000	-3.325	-1.803
	Legal Control	Upper Body	1.756*	.346	.000	.637	2.876
		Spokes	-.910	.288	.060	-1.842	.021
	Upper Body	Spokes	-2.667*	.265	.000	-3.525	-1.808

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Sidak.

*yellow highlight indicates significant effects.

Pairwise Comparisons

Measure: Conspicuity Rating

Light Placement	(I) Viewing Distance	(J) Viewing Distance	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Control	50 meters	100 meters	1.897*	.376	.000	.936	2.859
		200 meters	2.205*	.461	.000	1.026	3.384
	100 meters	200 meters	.308	.219	.435	-.254	.869
Lower Body	50 meters	100 meters	.974*	.250	.002	.335	1.614
		200 meters	2.333*	.389	.000	1.338	3.329
	100 meters	200 meters	1.359*	.298	.000	.596	2.122
Bike Frame	50 meters	100 meters	.962*	.283	.007	.237	1.686
		200 meters	1.705*	.423	.001	.622	2.788
	100 meters	200 meters	.744	.296	.055	-.014	1.501
Legal Control	50 meters	100 meters	.641	.313	.145	-.159	1.441
		200 meters	1.718*	.389	.001	.723	2.713
	100 meters	200 meters	1.077*	.361	.019	.153	2.001
Upper Body	50 meters	100 meters	.821	.358	.089	-.095	1.736
		200 meters	2.731*	.440	.000	1.604	3.857
	100 meters	200 meters	1.910*	.310	.000	1.116	2.704
Spokes	50 meters	100 meters	1.410*	.316	.000	.603	2.218
		200 meters	1.333*	.282	.000	.611	2.055
	100 meters	200 meters	-.077	.365	.995	-1.010	.856

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Sidak.

*yellow highlight indicates significant effects.

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