Accident Analysis and Prevention 45 (2012) 726–730

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Using reflective clothing to enhance the conspicuity of bicyclists at night

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ARTICLE INFO

Article history:
Received 20 June 2011
Received in revised form
14 September 2011
Accepted 27 September 2011

Keywords:
Conspicuity
Bicyclists
Clothing
Age
Bicycle lights

ABSTRACT

Bicycling at night is more dangerous than in the daytime and poor conspicuity is likely to be a contributing factor. The use of reflective markings on a pedestrian's major joints to facilitate the perception of biological motion has been shown to greatly enhance pedestrian conspicuity at night, but few corresponding data exist for bicyclists. Twelve younger and twelve older participants drove around a closed-road circuit at night and indicated when they first recognized a bicyclist who wore black clothing either alone, or together with a reflective bicycling vest, or a vest plus ankle and knee reflectors. The bicyclist pedalled in place on a bicycle that had either a static or flashing light, or no light on the handlebars. Bicyclist clothing significantly affected conspicuity; drivers responded to bicyclists wearing the vest plus ankle and knee reflectors at significantly longer distances than when the bicyclist wore the vest alone or black clothing without a vest. Older drivers responded to bicyclists less often and at shorter distances than younger drivers. The presence of a bicycle light, whether static or flashing, did not enhance the conspicuity of the bicyclist; this may result in bicyclists who use a bicycle light being overconfident of their own conspicuity at night. The implications of our findings are that ankle and knee markings are a simple and very effective approach for enhancing bicyclist conspicuity at night.

1. Introduction

Walking and bicycling are essential modes of travel and are promoted for their environmental, economic and health benefits. However, these modes of transport are not necessarily safe, and a review of data from a range of countries found that pedestrian and bicyclist fatalities account for nearly a third of all road users killed or seriously injured in road traffic crashes (Kwan et al., 2002). Through an analysis of Australian crash databases, Garrard et al. (2010) highlighted the vulnerability of Australian bicyclists by pointing out that fatality risk rates were between 4.5 and 18.6 times higher (per distance traveled), and injury risk rates 12.9 – 33.5 times higher for bicyclists than for car occupants.

Night-time bicycling is more dangerous than bicycling in daylight. For example, in a study of Swedish cyclists, 40% of bicyclist fatalities were reported to occur at night despite much lower exposure rates than in the day (Jaermark et al., 1991). A high proportion of bicycling fatalities are related to problems with frontal rather than rear conspicuity (Gale and Cairney, 1998). Motorists involved in collisions with bicyclists at night often state that they did not see the bicyclist until it was too late to stop in time (Blomberg et al., 1986; Räsänen and Summala, 1998). Crashes are also common when bicyclists expect drivers to give them right of way but drivers fail to yield. In many instances, this occurs because drivers do not see the bicyclist, either because they do not scan the road appropriately or because bicyclists are insufficiently conspicuous to drivers at night.

There is considerably more data on pedestrian than bicyclist conspicuity. Although the extent to which the data on enhancing the conspicuity of pedestrians generalizes to bicyclists is unknown, one approach seems particularly promising. There is considerable evidence that the perceptual phenomenon known as biological motion or biomotion – our visual sensitivity to patterns of human motion – can be utilized to enhance the night-time conspicuity of pedestrians (Balk et al., 2008; Blomberg et al., 1986; Owens et al., 1994; Wood et al., 2005). By placing inexpensive retroreflective markers on pedestrians' major joints (including ankles, knees, wrists, elbows, shoulders, etc.) that move during normal gait, drivers recognize the presence of pedestrians more frequently and at much longer distances. This is in sharp contrast to the relatively small benefits associated with the more typical practice of placing retroreflective material only on the chest, as in a retroreflective vest (Balk et al., 2007; Wood et al., 2005).

A key question is the extent to which these conspicuity advantages of biomotion reflective markings generalize to bicyclists.

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0001-4575/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aap.2011.09.038

The patterns of movement involved in bicycling are inherently different from those associated with being a pedestrian; while the movements associated with walking are constrained only by biomechanical forces, body movements associated with pedalling a bicycle are further determined by the structure of the bicycle. Despite the fact that the pedalling movements of the lower limbs are substantially different from the movements of a pedestrian's lower limbs, we hypothesize that highlighting the human form (by placing retroreflective markings on the bicyclist's ankles and knees) will provide conspicuity advantages to bicyclists at night.

The use of static or flashing front and rear bicycle lights is a widely adopted approach for improving bicyclist visibility at night and is now a legal requirement when bicycling on roads at night in many countries including Australia (National Transport Commission, 2009) and in many states in the USA. Interestingly, in our recent survey we found that bicyclists rate their own bicycle lights as more visible to drivers than do drivers themselves, especially at night (Wood et al., 2009a). However, while bicyclists are generally well-informed regarding the need to wear high visibility clothing, and are aware of the existence of visibility aids such as reflective vests, few bicyclists use such aids on a regular basis (Hagel et al., 2007; Wood et al., 2009b).

The present study explored whether positioning retroreflective markings on a bicyclist's ankles and knees provides significant night-time conspicuity benefits beyond that provided by a retroreflective vest alone. We measured the ability of drivers to recognize the presence of a bicyclist and varied clothing configuration, the presence or absence of a bicycle-mounted light and the age of the drivers.

2. Method

2.1. Participants

The sample of 24 participants consisted of 12 younger drivers (mean age 25.33 years ± 4.27 years, range 18–35 years; 6 men and 6 women), and 12 older drivers (mean age 72.5 years ± 5.02 years, range 66–80 years; 8 men and 4 women). The volunteers were recruited via presentations by the research team, recruitment notices placed on university noticeboards and participation in previous (unrelated) studies. All participants were licensed drivers and reported that they drove regularly. Participants passed the minimum Australian drivers' licensing criteria for binocular visual acuity of 6/12 (20/40) or better and wore the optical correction they normally wore while driving, if any. Participants were given a full explanation of the experimental protocols, and informed consent was obtained, with the option to withdraw from the study at any time.

Both visual acuity and contrast sensitivity were measured binocularly under photopic conditions. Distance visual acuity was assessed using the high contrast logMAR letter chart of the Berkeley Glare Test, at a viewing distance of one metre using an appropriate working distance correction. Visual acuity charts that express acuity as the logarithm of the minimum angle of resolution (logMAR) have become the standard for research and have many advantages including a logarithmic (rather than a variable) progression of letter sizes and line spacing, equal numbers of letters per line and letters of similar legibility (Bailey and Lovie, 1976). A visual acuity measurement of 6/6 (20/20) in traditional Snellen notation corresponds to a minimum angle of resolution (MAR) of 1 min of arc or a logMAR value of 0.00. Participants were instructed to read the letters from left to right on the chart and were encouraged to guess letters even when unsure. Visual acuity was scored on a letter by letter basis, where each letter correctly identified represented a score of −0.02 log units.

Letter contrast sensitivity was measured using the Pelli-Robson chart under the recommended viewing conditions (Pelli et al., 1988). This chart uses large letters which correspond to a spatial frequency of approximately one cycle/degree at a testing distance of one metre. As the observer progresses through the chart the letters become progressively fainter against their white background, by varying the contrast of the letters against the background in 0.15 log units steps, while the size of the letters remains constant. Participants were asked to read aloud as many of the letters as they could and were encouraged to guess a letter when they were unsure; each letter reported correctly was scored as 0.05 log units.

The mean visual acuity of the younger drivers was −0.11 logMAR (20/16, over a line better than 20/20), the mean for the older drivers was 0.04 logMAR (20/22, slightly worse than 20/20). This acuity difference between age groups was significant, $t(22) = 3.80$, $p = .001$. The mean Pelli-Robson score for the younger drivers was 1.90 log units while the mean for the older drivers was 1.65 log units, these differences in contrast sensitivity were also significant $t(22) = 7.18$, $p < .001$.

Participants reported 1–60 years of driving experience ($M = 28.63$ years). When questioned about night driving experiences over the previous year, younger participants reported that a larger portion of their total driving was at night relative to the older participants ($M = 34.67\%$ vs. 14%, respectively), $t(22) = 3.33$, $p < .05$.

2.2. Closed road test circuit and experimental vehicle

All testing was conducted under night-time conditions (i.e., after nautical twilight) on the closed road circuit at the Mt Cotton Driver Training Centre, which has been used in previous studies of vision and driving (e.g., Wood et al., 2009b; Wood and Troutbeck, 1994). All experimental sessions were conducted only on those nights when the road surface was dry and there was no precipitation. The circuit, which is representative of a rural road, consists of a two to three lane asphalt road and includes hills, bends, curves, lengthy straight sections and standard road signs and lane markings. The circuit does not feature any ambient lighting or traffic.

The experimental vehicle was an instrumented 1997 Nissan Maxima (right-hand drive, automatic transmission) that had been serviced (including headlight alignment to the European asymmetrical low-beam pattern standard) just prior to testing. A parallax-based video measurement system quantified the distance at which the participant recognized that a person was present in or near the roadway ahead (Jones et al., 1998; Tyrrell et al., 2009; Wood et al., 2005). The measurement system was linked to a touchpad inside the vehicle that recorded the moment at which the participant responded. Pre- and post-experimental calibration of the system confirmed the accuracy of the process.

The test bicyclist was located at the end of a 400 m straight section of three-lane roadway and positioned adjacent to glare lights, which consisted of a pair of stationary battery-powered car headlights mounted at a height and width typical of a sedan and were intended to represent the glare that would normally be created by an oncoming vehicle. To provide a degree of visual complexity, and also to act as distracters, 'clutter' zones (arrays of retroreflective objects such as cones and bollards) were positioned at three locations along the circuit (but not around the test bicyclist). To minimize expectancy effects, on some laps a second bicyclist was also positioned on the right shoulder at a different location of the circuit to that of the test bicyclist; three flashing amber lights surrounded this bicyclist, in addition to the previously mentioned 'clutter' to further add to the complexity of the road scene. The second bicycle was oriented in one of two directions for each lap. In the *away condition* the rear of the bicycle and bicyclist faced the approaching car and in the *sideways condition* the left side of the bicycle and bicyclist faced the oncoming vehicle. Response distances were not recorded for the second bicyclist because the roadway's geometry limited the sight distance; data relating to detection rates for the secondary bicyclist are reported elsewhere (Wood et al., 2010). Both bicyclists pedalled in place as the test vehicle approached; this allowed for the inclusion of naturalistic bicyclist motion while ensuring that the bicyclist was at the same location for each experimental run.

2.3. Clothing and bicycle conditions

For each lap the test bicyclist wore one of three clothing configurations, while the second bicyclist wore one of four clothing conditions. The *black condition* was a black sweatshirt and sweatpants and black shoe covers. The *vest condition* was the clothing from the black condition plus a lightweight yellow cloth mesh vest [Netti®] with silver retroreflective material on the shoulders and front and back totalling 375 cm^2 (the area facing the driver totalled 155 cm^2). The *vest, ankle and knee condition* was the clothing from the black and vest condition with the addition of 50 mm-wide silver retroreflective strips around the ankles and knees. With the vest included, the total area of retroreflective material facing the driver in this condition was approximately 755 cm^2. The fourth condition, worn only by the second (distractor) bicyclist was the *fluoro condition* and consisted of the clothing from the black condition with the addition of a fluorescent yellow bicycling vest with no retroreflective materials present.

For each lap the handlebar mounted lights on the bicycle used by the test bicyclist included one of three conditions. The *flashing condition* consisted of a white LED flashing at .5 s intervals (the bicycle also featured a rear-facing red LED), with both lights operating at 120 Hz. The *static condition* consisted of the same lights as above, but in a constant-on mode. In a third *no light condition* the bicycle light was absent; this served as a control condition. The test bicycle was also equipped with front white and red rear reflector along with amber pedal and spoke reflectors. The bicycle met the standards for night-time use as dictated by the Queensland Road Rules (Transport Operations (Road Use Management – Road Rules) Regulation 1999). The order of the clothing and bicycle light conditions were randomized for each participant.

2.4. Procedures

Each participant completed 11 laps of the test circuit, one practice lap and 10 data collection laps. The purpose of the first lap was to familiarize the driver with both the test vehicle and the circuit. At the start of each data collection lap, the participant was instructed to follow the specified route, to drive at a comfortable speed and to press a large (12 cm × 6 cm) luminous dash-mounted touch pad (and at the same time say "person!") as soon as he or she recognized that a person was present in the road scene ahead; participants were instructed not to respond until they were confident that what they saw was a person. To increase driver workload, participants were also instructed to read aloud all road signs that were encountered around the circuit. Performance on this task was not recorded or analysed. To minimize familiarity effects the order of the characteristics of the bicyclists (clothing and bicycle lighting) were varied randomly between participants and there was also a lap where there was no bicyclist present.

Two primary dependent variables are outlined here. The first is the percentage of trials in which the participant correctly identified the presence of the test bicyclist. A participant was said to have recognized a bicyclist if the driver pressed the response pad at any point along the approach to the bicyclist or immediately after having passed a bicyclist. The second dependent variable is the driver's response distance to the test bicyclist, which was defined as the distance from the test vehicle to the bicyclist at the moment the response pad was pressed.

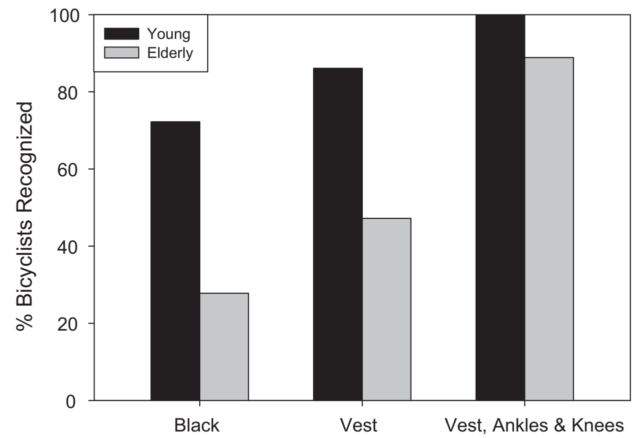

Fig. 1. The effect of bicyclist clothing and driver age on the percentage of bicyclists recognized.

The frequency with which participants correctly identified bicyclist was analysed using repeated measures logistic regressions (Generalized Estimating Equations – GEEs) with participant identity as a random factor, lighting condition (none, static, and flashing) and clothing (black, vest and vest, ankle and knees) as repeated measures factors, and age group (younger versus older) as a between-subjects factor with response (correct identification versus no correct identification) as a binomial criterion. GEEs were compared using independence, autoregressive (AR1). The exchangeable correlation structures using the QICC index, and the exchangeable structure was selected as it provided the best fit to the residuals. There were insufficient observations to permit a factorial analysis of the effects, and therefore the GEEs examined only the main effects of each variable. A three-way mixed factorial analysis of variance (ANOVA) was performed on the response distance data with the factors of age (2 between-subjects levels: young and older), clothing (3 within-subjects levels: black, vest, vest, ankle & knee), and bicycle light (3 within-subjects levels: none, static, and flashing). Since the response distances did not meet the assumption of sphericity required for univariate analysis of variance, data are reported using multivariate tests of significance which do not require this assumption.

3. Results

Overall, drivers responded to the presence of the test bicyclist on 70% of the laps, ranging from only 27% (black clothing, no lights, older drivers) to 100% (vest, ankle and knee for all light conditions, younger drivers). When the data were collapsed across the clothing conditions, the older drivers responded to only 55% of the bicyclists compared to 86% for the younger drivers, $\chi^2(1) = 6.9$, $p < .009$.

Importantly, the bicyclists' clothing strongly affected the drivers' ability to recognize their presence. Collapsed across driver age, drivers responded on 50% of the laps in the black condition, on 67% of the laps in the vest condition, and on 94% of the laps in the vest plus ankles and knees condition, $\chi^2(2) = 17.76$, $p < .001$; all pairwise differences were significant. Fig. 1 presents these data as a function of driver age. In the vest, ankle and knee condition, the vast majority of participants (both older and younger) were able to recognize the cyclists, whereas in the other conditions the older adults showed decreased ability to recognize the presence of a bicyclist. There was no significant effect of lights in terms of the proportion of bicyclists seen. Overall, participants recognized 75% of bicyclists

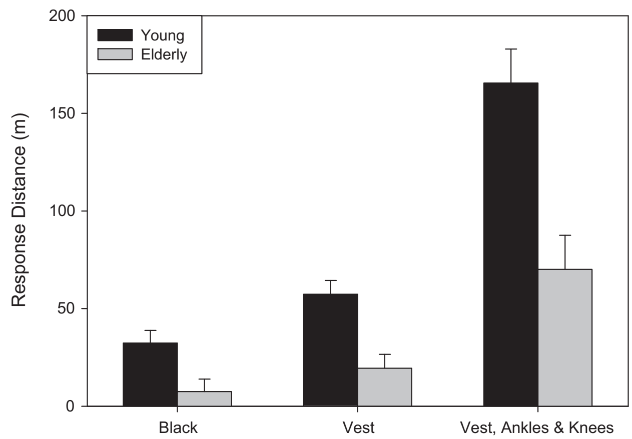

Fig. 2. Mean (+1 SE) distance at which the driver responded to the bicyclist as a function of the bicyclist's clothing and the driver's age.

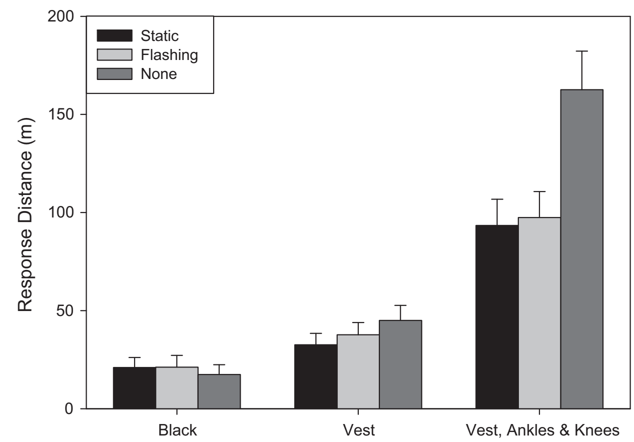

Fig. 3. Mean (+1 SE) distance at which drivers responded to the bicyclist as a function of the bicyclist's clothing and bicycle lights.

in the no-light condition, and 68% in each of the static and flashing conditions, $\chi^2(2) = 2.01$, $p = .367$.

Averaged across all bicyclist clothing and lighting conditions, drivers responded to the bicyclist at a mean distance of 58.7 m, ranging from 5.0 m (black clothing, older drivers, no lights) to 223 m (vest, ankle and knee, younger drivers, no lights). Fig. 2 represents the response distance data as a function of bicyclist clothing and driver age. This analysis revealed a significant main effect of age, $F(1,22) = 20.34$, $p < .001$, partial $\eta^2 = .48$, indicating that the overall mean from elderly drivers (32 m) was 2.7 times shorter than the mean from younger drivers (85 m). There was also a significant main effect of clothing, $F(2,21) = 36.16$, $p < .001$, partial $\eta^2 = .77$. Post hoc pairwise comparisons revealed that the visibility distances were significantly longer in the vest condition (38.4 m) than in the black condition (19.9 m), and longer in the vest, ankle and knee condition (117.8 m) than in either of the vest or black conditions. When the bicyclists were wearing the vest with ankle and knee reflectors they were seen at distances 5.9 times longer than in the black condition and 3.1 times longer than the vest only condition.

There was also a significant main effect of bicycle light, $F(2,21) = 15.93$, $p < .001$, partial $\eta^2 = .60$, such that the mean response distance was longer in the no-light condition (75.0 m) than in either the static (49.0 m) or flashing (52.1 m) light conditions. The static and flashing conditions did not differ significantly. The primary reason for the significant main effect of bicycle light was that the light, whether it was static or flashing, *decreased* response distances in the vest, ankle and knee condition relative to the no-light condition. This pattern may have resulted from the bicycle light (mounted on the handlebars) acting as a glare source that reduced the drivers' ability to see the reflective markings on the ankles and knees. Accordingly, there was also a significant interaction between clothing and bicycle light, $F(4,19) = 5.14$, $p = .006$, partial $\eta^2 = .52$, as can be seen in Fig. 3. Post hoc interaction contrasts showed that the difference between the vest condition and the vest, ankle and knee condition was greater in the absence of lights than in either the static or flashing conditions. The difference between the vest and black condition was also greater in the absence of lights than in either the static or flashing conditions.

There was also a significant two-way interaction between clothing and age, $F(2,21) = 4.67$, $p = .02$, partial $\eta^2 = .31$, as depicted in Fig. 2. Post hoc interaction contrasts revealed that the difference between the vest and the vest, ankle and knee condition was significantly greater for the younger than for the older participants, while the difference between the vest and black conditions did not depend on age.

4. Discussion

This study examined the influence of bicyclist clothing and lights on the visibility of bicyclists for drivers of different ages. The main motivation for this experiment was to determine whether retroreflective markings, which have been shown to increase pedestrian conspicuity (by facilitating the perception of their biological motion), would also be useful in making bicyclists more conspicuous to drivers at night. The data demonstrate that bicyclist clothing, bicycle lights, and driver age all significantly affect the ability of drivers to recognize bicyclists under real world night driving conditions.

There was a strong effect of clothing on the conspicuity of bicyclists. A key finding was that adding ankle and knee markings to a bicyclist who is already wearing a typical retroreflective vest provides a powerful conspicuity enhancement. This manipulation increased both the percentage of drivers who responded to the bicyclist and the distance at which the drivers responded. This finding supports the notion that clothing configurations that highlight the bicyclist's body movements have significant benefits and that they facilitate drivers of all ages to recognize bicyclists on the roads at night. Even though this configuration did not use a 'full' biological motion configuration, the effect was just as robust as the partial biomotion configurations used in prior studies of pedestrian conspicuity (e.g., Balk et al., 2007; Tyrrell et al., 2009). That the bicyclist in the present study wore the reflectors only on the ankles and knees and yet was still easily recognized suggests that 'full' biological motion configurations may not be necessary for the successful recognition of bicyclists, and that a convenient subset – marking just the ankles and knees – may be sufficient. This hypothesis is currently being explored in ongoing studies.

Drivers responded to the bicyclist wearing the reflective vest alone (38.4 m) at less than twice the distance of the bicyclist wearing only black clothing (19.9 m). The fact that this effect was not larger may surprise many bicyclists who rely on reflective vests at night. It is, however, consistent with existing data that demonstrate that pedestrians generally overestimate their own visibility at night, overestimate the conspicuity benefits of a retroreflective vest, and underestimate the conspicuity benefits provided by biological motion (Tyrrell et al., 2004). The relatively low conspicuity levels of the bicyclists when wearing the vest alone are likely to be attributable to the fact that retroreflective vests highlight neither the human form nor a recognizable pattern of motion that specifies a human.

While it is common for bicyclists to use bicycle-mounted lights in an effort to enhance their own safety at night, the present data suggest that such lights may not effectively facilitate drivers' ability to recognize that a bicyclist is present on the roadway ahead. Indeed, in the present data we found no evidence of a bicycle light (whether static or flashing) providing a conspicuity advantage in terms of whether the driver recognized the cyclist or not. While bicycle lights may be visible to drivers they appear not to facilitate drivers' awareness that a bicyclist is present (that is, they do not enhance bicyclist conspicuity). One surprising finding was that the vest, ankle and knee condition was particularly effective in improving conspicuity only in the absence of bicycle lights. This may be because there was only a narrow angle of separation between the bicycle light and the ankle and knee markings from the driver's perspective which appears to have resulted in the bicycle light acting as a glare source that reduced the effectiveness of the ankle and knee markings; the ankle and knee markings were maximally effective when the bicycle light was absent. Meanwhile, it is possible that bicyclists who use lights may unknowingly put themselves at risk by incorrectly believing that the conspicuity problem has been solved. Additional ongoing studies are quantifying bicyclists' beliefs about the effects of bicycle lights and clothing on their own conspicuity at night.

Older drivers were considerably worse at responding to the bicyclist than their younger counterparts; older drivers responded less often (55% vs. 86%) and their mean response distance was only 38% of the mean response distance for younger drivers. The poorer ability of older drivers to respond to the presence of bicyclists is likely to be related to changes in visual function, especially age-related changes in visual acuity and contrast sensitivity, which are exacerbated under low luminance conditions (Owsley, 2011). Given that the population of older drivers is increasing, these findings underscore the need for bicyclists to maximize their own conspicuity at night.

Overall, our findings highlight the fact that even alerted drivers commonly fail to recognize the presence of cyclists; the ability to respond to the unexpected appearance of cyclists is likely to be even worse. Our data also confirm that positioning reflectors on a bicyclist's ankles and knees – a convenient and inexpensive intervention – effectively enhances bicyclist conspicuity for both younger and older drivers. Although additional research should explore the value of strategically placed reflective markers on bicyclists in different night-time contexts (e.g., on different types of roadways and scenarios and under varying illumination conditions) the present data suggest that their benefits are likely to be substantial and apply whether a bicycle light is present or absent. Indeed, a bicycle light by itself was shown to have a considerably smaller effect on bicyclist conspicuity. Collectively, these data provide an important advance in understanding and reducing the conspicuity problems faced by bicyclists who choose to cycle in the hours of darkness, either for recreational or work purposes.

Acknowledgements

This research was funded by an Australian Research Council Linkage Grant. The authors would like to express appreciation to Queensland Transport for allowing the use of the facilities at the Mt Cotton Driver Training Centre and to the staff of the Mt Cotton Centre for their generous cooperation and support.

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