TITLE: Making night-time pedestrians safer using innovative clothing designs

Authors: Alex A. Black [1], Dean Brough [2], Mark King [3], Neil King [4], Laura A Bentley [1], Fiona Fylan [5], Joanne M. Wood [1]

Affiliations :

[1] Centre for Vision and Eye Research, School of Optometry and Vision Science, Queensland University of Technology (QUT), Australia

[2] School of Design, QUT, Australia

[3] Centre for Accident Research and Road Safety-Queensland (CARRS-Q), QUT, Australia

[4] School of Exercise and Nutrition Sciences, QUT, Australia

[5] Leeds Sustainability Institute, Leeds Beckett University, Leeds, United Kingdom

Corresponding Author: Dr Alex Black

School of Optometry and Vision Science,
Queensland University of Technology
Victoria Park Road, Kelvin Grove, Brisbane, QLD 4059, Australia
Email: aa.black@qut.edu.au

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ABSTRACT

Night-time pedestrians, including recreational walkers and runners, remain at significant risk of being killed or seriously injured, because drivers often fail to see them in time to avoid a collision. Clothing incorporating retro-reflective markers on the moveable joints creates a visual perception of “biomotion” which has been shown to improve night-time pedestrian conspicuity. This study investigated whether clothing with markings in the biomotion configuration retains its conspicuity if adapted to include thinner or patterned retro-reflective strips making it more acceptable to wear for recreational pedestrians. In a night-time closed road study, the relative conspicuity of pedestrians to 14 young drivers with normal vision (mean age 24.3 ± 3.1 years) was assessed for pedestrians wearing different thicknesses and patterns of biomotion strips and compared with typical clothing worn by night-time pedestrians, including commercially available sports clothing with retro-reflective elements, fluorescent yellow top, and black clothing. Results showed that all the biomotion configurations resulted in significantly longer recognition distances: around 2 times longer than sports clothing, 2.5 times longer than fluorescent top and 4 times longer than black clothing. Similar trends were found for the distance at which drivers correctly identified pedestrian orientation (towards or sideways to the vehicle), with significantly longer distances for all the biomotion configurations, when compared to the sports, fluorescent top and black clothing. These findings highlight the effectiveness of biomotion clothing, even when using retro-reflective strips as thin as 0.75cm and have implications for clothing designs for recreational walkers and runners to enhance their night-time safety.

1. INTRODUCTION

Pedestrians continue to be at significant risk of being injured or killed as a result of a collision with a vehicle at night-time (Kwan & Mapstone, 2006), with poor conspicuity to drivers being a leading risk factor (Owens & Sivak, 1996). The extent of the problem is demonstrated in recent data reports, with the number of night-time pedestrian fatalities increasing by 67% in the United States, over the 2009 to 2018 period (Retting, 2020). In another US study of pedestrian fatalities, pedestrians were 5 times more likely to be fatally injured at night compared to during the day; the absence of streetlighting also increased night-time fatality risk by 2.4 times when compared to locations with streetlighting (Ferenchak et al., 2022). Similar trends were reported recently in Australia, with the odds of a fatal pedestrian injury being 2.9 times higher in dark streets with lights and 7.9 times in dark streets without streetlights compared to daytime (Nasri et al., 2022).

The visual limitations of drivers at night are a key factor contributing to poor pedestrian conspicuity (Tyrrell et al., 2016; Wood, Lacherez, et al., 2014), even for drivers with normal vision, as low contrast pedestrians are challenging to detect and recognise from safe distances. Therefore, it remains important for pedestrians to be proactive in increasing their conspicuity for their own safety.

Studies have established that the conspicuity of pedestrians can be optimised by using retro-reflective markings located on the pedestrian's extremities, particularly on the moveable joints (wrists, elbows, ankles, knees) to create the perception of "biological motion" or "biomotion" for drivers (Wood, Marszalek, et al., 2014; Wood et al., 2017). These clothing strategies take advantage of humans' perceptual ability to recognise the unique patterns of motion of human gait (Johansson, 1973). Furthermore, the retro-reflective material uses the vehicle headlighting to reflect light back to the driver, and thus can be used under any night-time roadway situation, with or without streetlighting. Importantly, retro-reflective strips are a low-cost, low-tech solution, using currently available materials, and avoid the need for additional wearable lighting devices. Accordingly, there is an increase in the range of sports clothing incorporating some retro-reflective elements, although not typically in a biomotion configuration, thus their conspicuity benefits are likely to be sub-optimal. Furthermore, focus group research has reported that cyclists and runners believe that fluorescent clothing is more visible at night (Fylan et al., 2020). Fluorescent materials rely on ultraviolet light available in natural daylight to generate visible light, yet this effect is not present at night, with research demonstrating its limited conspicuity compared to retro-reflective materials in night-time cycling visibility research (Wood et al., 2013).

Efforts to increase conspicuity of pedestrians need to consider all types of pedestrians who interact with roadways at night. This includes roadworkers, who are particularly vulnerable due to the nature of their work on the roadway, as well as recreational walkers or runners who may need to interact with the roadway and moving vehicles when crossing the road. Research has demonstrated the significant benefits of retro-reflective material in the biomotion configuration in roadworkers, using 5cm wide retro-reflective strips sewn into clothing at the moveable joints (Wood, Marszalek, et al., 2014; Wood et al., 2011). Importantly, these forms of biomotion marking have been incorporated into safety standards for high-risk applications such as roadworkers (King & Wood, 2013; Standards Australia, 2011).

Recreational walkers or runners, however, remain largely unaware of effective strategies to increase their conspicuity at night, as found in recent focus group research (Fylan et al., 2020); it was also reported that the roadworker-type outfits using wide retro-reflective strips, are less appealing to wear in these recreational pursuits. As such, the design of suitable clothing configurations needs to consider various factors, such as aesthetic appeal, functionality, and cost (Fylan et al., 2021). For example, the use of thinner retro-reflective markings in the biomotion configuration, using 2.5 cm wide strips, showed equivalent levels of accuracy in judging pedestrian walking direction when compared with standard 5 cm wide strips (Wood et al., 2021). However, to date, no research has examined the effect of modifications of biomotion-enhanced clothing, such as thinner strips or patterns, on pedestrian visibility distances, with the aim to develop more acceptable designs for recreational pedestrians. Furthermore, an important benefit of biomotion markings surrounding the moveable joints is the conspicuity benefits present in all directions in which a pedestrian may interact with a vehicle, however, these benefits have not been explored to date.

This aim of this study was to assess the conspicuity benefits of various biomotion retro-reflective clothing configurations, using reduced width and patterns of the retro-reflective strips to improve their appeal, and compare these designs to clothing commonly used by recreational pedestrians at night, including commercially available sports clothing with embedded retro-reflective markings, fluorescent yellow tops, and black clothing.

2. METHODS

2.1.Participants

Participants included 14 young, licenced drivers (mean age 24.3 ±3.1 years, range 19-28 years, 71% female), who had normal vision with binocular visual acuity of 6/6 or better (Snellen equivalent), with habitual optical correction if used for driving. The study adhered to the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the nature of the study and experimental procedures, and written informed consent was obtained.

2.2.Experimental Design and Procedure

Testing was conducted on a closed-road circuit at the Mt Cotton Driver Training Centre (South-East Queensland, Australia) at night after nautical twilight and when road surfaces were dry. The section of the circuit used for this study was a 1-km long circular loop which included standard road signs and markings. The circuit did not have any streetlighting and was free of any other vehicles.

Two experimenters acted as pedestrians and 'walked in-place 'at two different locations on the opposite side of the road from the oncoming vehicle, which allowed for inclusion of naturalistic motion and ensured pedestrian safety (**Fig 1**). The location of one pedestrian (Ped 1) was along a three-lane road section, while the other pedestrian (Ped 2) was located along a two-lane road section.

Figure 1: Schematic of the laps indicating start/finish location, the location of the two pedestrians (main and alternate positions), and direction of travel indicated by yellow arrows.

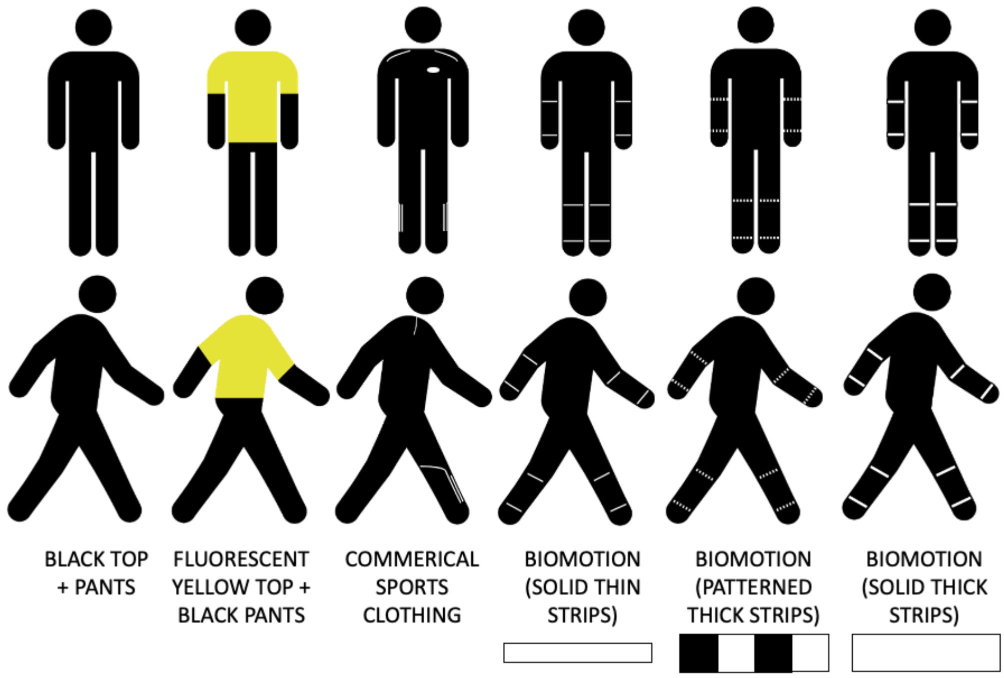

Figure 2: Schematic of the clothing configurations of the pedestrians as seen by the driver of the experimental vehicle. The solid thin strips were 0.75 cm wide, while the solid and patterned thick strips were 1.5 cm wide.

Participants drove an instrumented automatic vehicle (2017 Toyota Camry) with the headlamps on low-beam setting, for 14 test laps, following a practice lap to familiarise the driver with the vehicle and practice the pedestrian task. For each test lap, the two pedestrians wore one of six clothing conditions: three biomotion configurations with retro-reflective strips 1.5 cm wide (thick-solid), 0.75cm wide (thin-solid), or 1.5 cm patterned (thick-patterned), as well as conditions with black pants and either a black top (black), or a fluorescent yellow top, and one commercially-available sports outfit incorporating some retro-reflective material (shoulder and chest logo strips, and strips on the lower, lateral leg), as shown in **Fig 2**. To assess the impact of pedestrian walking direction on conspicuity, the pedestrians walked in place at the roadside in one of two orientations:

- Facing towards the oncoming vehicle ("towards"),
- Facing towards the centre of the road, thus sideways to the oncoming vehicle ("sideways").

The approximate surface area of retro-reflective material in the clothing conditions differed between the pedestrian clothing conditions and their orientation: sports clothing (towards = 45cm^2; sideways = 29 cm^2), biomotion thin-solid (towards = 39cm^2; sideways = 39cm^2), biomotion thick-patterned (towards = 39cm^2; sideways = 39cm^2), biomotion thick-solid (towards = 78cm^2; sideways = 78cm^2).

Each of the clothing configurations and orientations was presented twice in a random sequence, and the pedestrians wore different configurations on each lap. In addition, to reduce drivers' expectations that a pedestrian would always be located at the same location, each pedestrian was positioned at an alternate location as a distractor for 1 of the 14 laps (which was not used for analysis), and each of the pedestrians was absent for 1 of the 14 laps. Therefore, in 4 of the 14 laps, either one of the pedestrians was either absent or positioned at an alternative location to that of the other laps.

Drivers tapped a response pad when they first recognised a pedestrian was present on the side of the road (recognition task) and a second time when they identified the walking direction of the pedestrian, either facing towards the driver or sideways (direction identification task). An in-vehicle GPS logging system recorded the location of the vehicle on the circuit when drivers pressed the response pad. Pedestrian recognition and direction distances were calculated from the known GPS coordinates of pedestrians and the GPS coordinates of the car when drivers tapped the touchpad for the pedestrian recognition and direction tasks.

2.3.Statistical analysis

Statistical analyses were performed using SPSS version 28.0 (SPSS, Chicago, IL), and the level of significance was set at $p<0.05$. Descriptive sample statistics are reported as mean and standard deviations (SD). To account for the repeated measures study design, separate Linear Mixed Models (LMM) were conducted for pedestrian recognition and direction identification distances, each including fixed effects for clothing configuration (6 levels), orientation (2 levels: towards, sideways), a clothing x orientation interaction term, and a pedestrian factor (2 levels: Ped 1 and Ped 2) to account for any differences between the two pedestrian locations. All LMM models included random intercepts for participants, to take into consideration the repeated measures design, and used maximum likelihood estimation. Significant interactions in these models were tested using simple effects models and pairwise comparisons to understand the nature and direction of these relationships. Due to the exploratory nature of this study, no correction for multiple comparisons was performed.

3. RESULTS

The mean pedestrian recognition and direction identification distances for the six clothing conditions, and the two pedestrian orientations, are presented in **Table 1 and Fig. 3**.

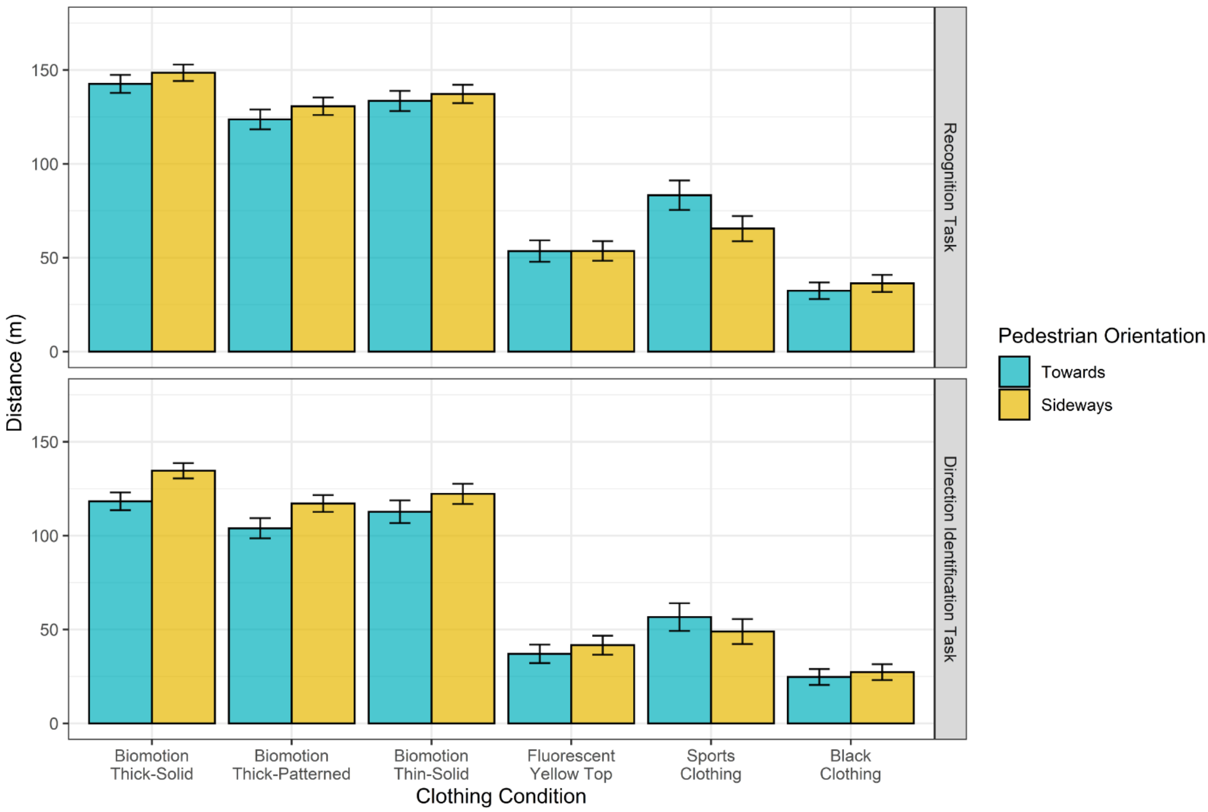

Figure 3: Pedestrian recognition and direction identification distances, as a function of clothing condition and pedestrian orientation. Error bars represent one standard error of the mean.

Table 1: Mean (SD) recognition and direction identification distances (in metres), as a function of clothing condition and pedestrian orientation

Pedestrian Orientation	**Biomotion clothing (thick-solid strips)**	**Biomotion clothing (thick-patterned strips)**	**Biomotion clothing (thin-solid strips)**	**Sports Clothing**	**Fluorescent Yellow Top and Black Pants**	**Black Top and Pants**
Detection Task						
Towards	142.6 (25.4)	123.7 (28.0)	133.5 (28.4)	83.3 (41.5)	53.5 (30.1)	32.4 (23.3)
Sideways	148.5 (23.1)	130.7 (24.7)	137.2 (25.9)	65.5 (35.5)	53.6 (27.7)	36.3 (24.2)
Direction Identification Task						
Towards	118.3 (25.0)	104 (28.5)	112.7 (32.1)	56.6 (38.9)	37.1 (25.9)	24.7 (22.4)
Sideways	134.6 (21.6)	117.1 (23.8)	122.3 (28.5)	48.9 (35.2)	41.7 (26.8)	27.3 (22.5)

For the recognition task, clothing had a significant effect on pedestrian recognition distances ($F(5, 322)=252.1$; $p<0.001$), where the three biomotion clothing configurations provided significantly longer recognition distances compared to the sports, fluorescent yellow top or black clothing (Figure 1). Overall, pedestrians wearing any form of biomotion clothing were recognised at around 2 times longer distances than the sports clothing (~135m vs ~74m), around 2.5 times longer than the fluorescent yellow top (~135m vs ~54m), and around 4 times longer than the black clothing (~135 m vs ~35 m); all $p<0.001$. In the pairwise comparisons, the thick-solid strips in the biomotion configuration provided slightly longer, but significant, recognition distances compared to the thin-solid or thick-patterned biomotion configurations (~10 to 18 m shorter than the thick-solid configuration, $p<0.015$). There were also significant differences between the sports, fluorescent yellow top, and black clothing conditions (all $p<0.001$), with the sports clothing providing longer recognition distances, then the fluorescent yellow top, followed by the black condition.

There was no significant effect of pedestrian orientation on recognition distance ($F(1,322)=0.04$; $p=0.85$), but there was a significant interaction of clothing and orientation

(F(5,322)=2.5; p=0.034). This interaction was largely due to differential effect of pedestrian orientation in the sports clothing condition (p=0.001), where the recognition distance was 17.8 m longer when the pedestrian faced the vehicle compared to sideways (83.3m (SD 41.5m) vs 65.5m (SD 35.6m)). There was also a small, but significant, differential effect of pedestrian orientation for the black clothing condition (p=0.031), where the recognition distance was 3.9 m greater when the pedestrian faced sideways compared to towards (36.3 m (SD 24.2m) vs 32.4 (SD 23.3m)). There was no effect of pedestrian orientation on recognition distances for the three biomotion clothing configurations, or for the fluorescent yellow top (p>0.18).

Clothing had a significant effect on direction identification distances (F(5,322)=263.0, p<0.001), where all the biomotion clothing configurations resulted in significantly longer direction identification distances than the sports, fluorescent yellow top or black clothing configurations (Figure 1). Overall, drivers were able to identify the direction of pedestrians wearing any form of biomotion retro-reflective strips at around 2 times longer distances than sports clothing (~118m vs ~52m), around 3 times longer than fluorescent yellow top (~118m vs 39m), and around 4.5 times longer than black clothing (~118 m vs 26m). In the pairwise comparisons, the thick solid biomotion provided slightly longer, but significant, recognition distances compared to the other two biomotion configurations (~9 to 16 m shorter than the solid thick configuration, p<0.021). The sports, fluorescent yellow and black clothing conditions showed differences between each other, with the sports clothing providing the longest direction identification distances, then the fluorescent yellow, followed by the black (all differences p<0.001).

There was a significant effect of pedestrian orientation on direction identification distance (F(1,322)=8.3, p=0.004), and a significant interaction between clothing and orientation (F(5,322)=2.5, p=0.032). This interaction was largely due to the differential effect of orientation in the biomotion thick-solid (p=0.002) and biomotion thick-patterned (p<0.024) conditions, where the direction identification distance was around 13 to 16 m longer when the pedestrian was walking sideways compared to towards the oncoming vehicle. There was no difference in direction identification distances for the other clothing configurations ($p>0.07$).

4. DISCUSSION

In this study, we evaluated the conspicuity benefits of various novel biomotion retro-reflective clothing configurations, using thinner strips and patterned strips to improve their cosmetic appeal, as well as conditions including black pants with either a black top, a fluorescent yellow top, or a commercially available sports clothing containing some retro-reflective material. The findings demonstrated that the biomotion configuration provided significant conspicuity benefits compared to the other configurations, both for recognition and direction identification distances. While the presence of some retro-reflective markings in the sports clothing provided some conspicuity benefits, this was significantly lower than the benefits provided by any of the full biomotion configurations, regardless of the thickness or pattern of the strips. As expected, the configurations without any retro-reflective markings (fluorescent yellow top, or black clothing) conferred poorer conspicuity benefits, with mean recognition distances around 35 to 55 m. When considered in the context of on-road driving, the stopping distance for a vehicle travelling at 60 kilometres per hour (~40 miles per hour) is around 45 m in dry conditions (Queensland Government, 2022), highlighting the challenges faced by drivers to detect and recognise low-contrast pedestrians at safe distances (without retro-reflective markings), even in this young driver cohort with normal vision and no ocular conditions. Importantly, it is likely that recognition distances would be shorter in older drivers, and in those with visual impairment, given the significant detrimental effect on pedestrian recognition in older drivers when compared to younger drivers, both without and with blurred vision (Wood et al., 2015).

All three of the biomotion clothing configurations provided strong conspicuity benefits, consistent with previous studies demonstrating the conspicuity benefits of the biomotion configuration using retro-reflective strips, including earlier attraction of driver attention (Wood et al., 2017), and longer recognition distances (Wood et al., 2015; Wood, Marszalek, et al., 2014). In the current study, there were small but significant improvements with the thicker retro-reflective strips, although the thinner or patterned strips still demonstrated strong conspicuity benefits, indicating that these more appealing biomotion designs could be used to enable safe detection distances, while also addressing the desire for appealing designs highlighted in previous focus group research (Fylan et al., 2020). Importantly, the configurations used in the current study still provided excellent conspicuity benefits, even when using thinner strips (0.75 to 1.5 cm strips), which are more cost effective and practical, than road worker clothing (5 cm strips).

In addition, there was an enhanced benefit with the biomotion configurations for the sideways walking direction, whereby the movement of the arms against the body is likely to have provided important visual cues to guide identification of walking direction. This would reflect a pedestrian's orientation to a driver if the pedestrian were to walk across the roadway in front of the vehicle. This finding provides further evidence of the benefits of the biomotion configuration in improving conspicuity, ensuring that both the presence and intention of the pedestrian are clear to the driver, so they can make appropriate actions to avoid a collision.

In this study, the presence of some retro-reflective material on the sports clothing did provide some conspicuity benefits, with twice the recognition distance than the black configuration. However, the conspicuity benefits remained significantly lower when compared to all of the biomotion configurations. This finding may have been due to the variation in the distribution of reflective strips, located on the lateral section of the lower legs and the shoulders, and does not follow the biomotion configurations, thereby not providing consistent levels of reflectivity in the different orientations, hence the differential recognition distances for the towards and sideways directions. As such, clothing manufacturers need to consider the placement of retro-reflective strips on clothing and ensure the quantity and quality of retro-reflective materials on garments.

The findings of this study provide further evidence to support the education of recreational pedestrians regarding the benefits of conspicuity aids at night, especially as they may overestimate their own visibility to approaching drivers at night, compared to their actual visibility (Tyrrell et al., 2004). In particular, understanding the differential effect of these clothing configurations in terms of improving the capacity of oncoming drivers to both recognise the presence of pedestrians and identify their walking direction in road systems will provide recreational pedestrians with the evidence to inform their selection of biomotion-enhanced clothing when on the roadways at night, and their decision to invest in these designs to increase their conspicuity to enhance their safety.

We do, however, acknowledge that the conspicuity of pedestrians is not the only determining factor for safety on night-time roads. These include driver-related factors, such as alcohol and drug use and visual characteristics (Owens & Sivak, 1996; Sanders et al., 2022; Wood et al., 2015) and road design characteristics, such as higher-speed roadways and lack of streetlighting (Ferenchak et al., 2022; Nasri et al., 2022). As such, strategies for pedestrians to proactively increase their own conspicuity remain important, given the increasing numbers of pedestrian fatalities (Retting, 2020). We have developed the acronym ‘WAKE’ to describe this biomotion clothing, given that it comprises reflective elements on the Wrists, Ankles, Knees and Elbows, and the term could be included in future safety awareness campaigns, such as ‘WAKE-UP to Pedestrian Safety’.

Although the results in this study have important implications for the safety of pedestrians on the road at night, they must be considered in the light of some study limitations. Firstly, the use of pedestrians walking in place on the opposite side of the road to the oncoming vehicle, rather than moving across the roadway, as would be the case under real-road conditions. However, this location relative to the driver is still a relevant scenario for a driver to detect a pedestrian, and similar patterns of findings would be likely if the pedestrian was on the same side of the road as the vehicle. The clothing configurations were not matched for surface areas of retro-reflective materials, as the aim was to explore commonly used clothing configurations. An important finding, however, was the positioning of the strips was more important than surface area; for example, the bio thin-solid and thick-patterned provided similar conspicuity benefits to the bio thick-solid, even though they included half the surface area of retro-reflective material. Studies have also shown that thinner retro-reflective markings (2.5 cm wide strips) in the biomotion configuration, showed equivalent levels of accuracy in judging pedestrian walking direction compared to 5 cm wide strips (Wood et al., 2021).

Importantly, the pedestrian clothing conditions used in this study were presented under real night-time road conditions when participants were driving an actual vehicle which is an important strength of this study, as night-time driving conditions are difficult to replicate in simulators. These difficulties arise due to limitations in simulators' ability to render the required luminance levels and spatial/temporal resolution to reflect the adaptation levels for night-time driving, and cannot accurately model the light reflected from retro-reflective strips illuminated by a moving headlight beam (Wood & Chaparro, 2011).

In summary, clothing incorporating retro-reflective strips in a biomotion configuration, even when strip width was as thin as 0.75 cm, which can be incorporated into recreational sports clothing, significantly improved night-time conspicuity. These effects were evident regardless of pedestrian orientation and have significant implications for better design of clothing for recreational walkers and runners to enhance their safety on night-time roads.

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