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Is drivers' interaction with pedestrians affected by cognitive load and LED bands? A driving simulator study investigating performance across two age groups during different ambient lighting conditions ☆

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ABSTRACT

Pedestrians, being vulnerable road users, are disproportionately affected by road traffic crashes. Many factors influence driver-pedestrian interactions and hence pedestrian safety. Within these interactions, drivers play a critical role as operators of the vehicle. Therefore, it is crucial to understand what factors influence drivers' perceptions and actions when interacting with pedestrians in different situations. A driving simulator study was designed to investigate the effects of age (younger and older drivers), cognitive load (no task, 2-back task), the presence (or absence) of a zebra crossing, ambient lighting (daylight, after dark), pedestrian position (standing, walking), and whether the pedestrian was wearing a light-emitting diode (LED) band on drivers' yielding behaviours during interactions with pedestrians. Two groups of drivers (23 younger drivers: $Mdn_{age} = 22$ and 19 older drivers: $Mdn_{age} = 64$) completed two experimental drives during daylight and after dark. Objective measures (probability of yielding and average deceleration) were used to interpret yielding behaviour and the factors influencing it. The results showed that drivers were more likely to yield when a zebra crossing was present. For conditions with zebra crossings, drivers were more likely to give way to pedestrians waiting by the crossing than when pedestrians were approaching the crossing. Drivers of both age groups behaved in a similar way with standing pedestrians. But with walking pedestrians, younger drivers were more likely to yield and did so softer. In trials where the pedestrians wore LED bands to enhance their conspicuity, the average deceleration was reduced, resulting in smoother braking. These results inform the development of policy and interventions (e.g., effectiveness of zebra crossings, effects of LED bands) to improve the safety of vulnerable road users.

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1. Introduction

Road users such as drivers, pedestrians, cyclists and e-scooter riders regularly interact with each other during their daily journeys. Markkula et al. (2020, p. 737) defined these interactions as "*a situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future*". In some situations, these interactions may lead to conflicts between road users and may result in negative outcomes such as crashes and near misses. Among the range of road users, vulnerable road users (e.g., pedestrians) are highly affected by road traffic crashes. Worldwide, more than half of all road traffic deaths were found to be among vulnerable road users in 2021 (World Health Organisation, 2023), with pedestrians representing around 20–25 % of all fatalities across the world.

Both naturalistic (e.g., Cloutier et al., 2017; Gorrini et al., 2018; Madigan et al., 2021) and simulator (e.g., Bella et al., 2017; Kalantari et al., 2023; Lubbe & Davidsson, 2015) studies have shown that during driver-pedestrian interactions, many individual and environmental factors play a role in determining the outcome of the interaction (e.g., Amado et al., 2020; Kalantari et al., 2023; Kutela et al., 2023; Schneider & Sanders, 2019). For example, in the United Kingdom, in those collisions recorded where a police officer attended the scene, driver error/reaction (e.g., failure to look) or behaviour (e.g., reckless driving) were some of the most common contributory factors for pedestrian fatalities in 2023 (Department for Transport, 2024; 2025). Among these, driver age (e.g., Lee & Abdel-Aty, 2005), and distraction of either the drivers (e.g., Sundfør et al., 2019) or pedestrians (Hossain et al., 2024) are prominent, with environmental features also playing a role.

1.1. Driver age

Drivers' age is one factor influencing response to peripheral hazards (e.g., Folli & Bennett, 2023; Ranchet et al., 2022), such as pedestrian detection. Older people tend to respond more slowly to the onset of targets and detect fewer targets than do younger people (Fotios et al., 2021). With advancing age, drivers' hazard perception skills deteriorate (Folli & Bennett, 2023), leading to an elevated risk of crash involvement due to reduced useful field of view (Anstey et al., 2005; Rogé & Pébayle, 2009). Studies in this context show that, overall, younger and older drivers are the most at-risk groups (Santolino et al., 2022).

However, there are contradictory findings regarding the differences in driving performance of different age groups. While some studies have demonstrated that older drivers exhibit slower reactions and reduced capacity for vehicle control (Singh & Kathuria, 2021), others (Borowsky et al., 2009, 2010) have highlighted improved hazard perception skills of older and more experienced drivers in comparison to novice drivers (e.g., Lee et al., 2008; Ranchet et al., 2022). Possibly due to a lack of experience, younger drivers are involved in a high number of non-fatal crashes, which is linked to unsafe driving behaviours or failure to recognise potential hazards (McKnight & McKnight, 2003). However, according to results from an on-road study conducted by Wood et al. (2005), while nearly 85 % of pedestrians were detected by younger drivers (21–34 years old), this figure dropped to just over 53 % for older drivers (60–75 years old).

It is imperative to acknowledge the significant risks associated with both younger and older groups (Karthaus et al., 2020; Santolino et al., 2022) and provide comparative insights into distinct risk mechanisms, enabling targeted interventions tailored to the unique vulnerabilities of younger and older drivers. For example, younger drivers often face challenges due to their lack of experience (e.g., Rolison & Moutari, 2020) and limited hazard perception skills (i.e., Evans et al., 2022). In contrast, older drivers may encounter age-related declines in perceptual, cognitive, and motor functions (e.g., Dawson et al., 2010; Depestele et al., 2020; Rogé & Pébayle, 2009; Wagner & Nef, 2011). The study reported here therefore recruited participants from younger and older age groups to study differences in their hazard perception capabilities when driving in two different ambient lighting conditions (depicting daylight and after dark conditions).

1.2. Driver distraction

Driver inattention, including distraction, is another contributory factor in collisions in the UK (Department for Transport, 2025) and worldwide (e.g., Klauer et al., 2006; Robbins & Fotios, 2022) and increases crash and near-crash involvement (Jazayeri et al., 2021; Zhang et al., 2022). Driver distraction is defined as the diversion of drivers' attention from essential driving tasks to other activities, whether related or unrelated to driving (Regan et al., 2011). Driver distraction can involve activities which take the driver's eyes (i.e., visual distraction), attention (i.e., cognitive distraction), and hearing (i.e., auditory distraction) off the road and/or hands and feet away (i.e., manual distraction) from vehicle control (either in isolation or combined – Hallett et al., 2011, as cited in Oviedo-Trespalacios & Regan, 2021). Engaging in activities, such as hands-free mobile phone conversations, can result in "cognitive distraction" (Regan, 2010, as cited in Regan & Oviedo-Trespalacios, 2022); the diversion of attention to thoughts other than driving.

While vision and perception play an important role in driving, cognitive distraction is also shown to have its deleterious effects. These include higher concentration of gaze towards the road centre (Kountouriotis & Merat, 2016) and reduced visual scanning of the surrounding environment (Engström et al., 2005). This can lead to delayed hazard detection (D'Addario & Donmez, 2019), including impaired detection of peripheral targets (Öztürk et al., 2023), as demonstrated in the Detection Response Task (International Organization for Standardization, 2016), or pedestrians (Choudhary & Velaga, 2017; D'Addario & Donmez, 2019; Haque & Washington, 2014). In an observational study, Krizsik and Sipos (2024) determined that distraction significantly affects drivers' willingness to yield at designated pedestrian crossings. Specifically, when drivers are distracted, they exhibit a reduced willingness to yield. Khan and Habib (2022) demonstrated that driver distraction on straight roads exacerbates the severity of pedestrian injuries.

1.3. The effect of zebra crossings, pedestrian position/conspicuity, ambient lighting

In terms of drivers' response to pedestrians, results of studies from developed countries such as the UK, Sweden, Czech Republic and the United States show that formal road infrastructure (e.g. pedestrian crossings), the level (i.e. luminance) of road lighting, pedestrian position and pedestrian conspicuity all affect the speed of driver response to crossing pedestrians. For example, both naturalistic (Leden et al., 2006; Mitman et al., 2008) and simulator (Kalantari et al., 2023) studies have found an increased likelihood of drivers yielding to pedestrians in the presence of zebra crossings. The position of pedestrians is an additional factor influencing driver-pedestrian interaction (Al-Kaisy et al., 2018), with a higher likelihood of drivers' yielding to pedestrians waiting in closer proximity to the roadside (Al-Kaisy et al., 2018; Sucha et al., 2017).

In terms of ambient lighting, pedestrian injuries (Kemnitzer et al., 2019; Pour-Rouholamin & Zhou, 2016; Salon & McIntyre, 2018) and fatalities (Hebert Martinez & Porter, 2004) are known to increase after dark and due to poor lighting/visibility of the driving environment. Although studies show that drivers reduce their average speed after dark (Owens et al., 2007), they also elicit fewer fixations to safety–critical areas (Garay-Vega et al., 2007) and have reduced recognition of road signs (Owens et al., 2007). This difference between daylight and after dark driving may be due to the increased cognitive demand posted by higher visual workload to offset impaired visual function at lower levels of lighting (Yared & Patterson, 2020).

Finally, pedestrian conspicuity (i.e., the degree to which a pedestrian draws attention and stands out from their surroundings, beyond mere visibility) is an important determinant of driver response and interaction with pedestrians (e.g., Tyrrell et al., 2016). Pedestrians, especially those with dark clothing, are involved in more crashes when lighting is limited (Hossain et al., 2023), with several studies recommending enhanced pedestrian visibility and illumination to improve their safety (e.g., Anderson et al., 2022; Owens et al., 2007; Wood, 2020; 2023).

To mitigate these crashes, interventions, such as retroreflective materials on the joints, have been utilised to improve pedestrian visibility and/or conspicuity (e.g., Bhagavathula & Gibbons, 2023; Black et al., 2023; Kwan & Mapstone, 2004; Wood, 2023; Wood et al., 2017). Previous studies have emphasised the significance of pedestrian clothing for detection by drivers, with LED bands that mark biomotion, enhancing pedestrian conspicuity by capturing driver attention (Black et al., 2023; Wood et al., 2005). For instance, Wood et al. (2005) investigated the visibility of pedestrians with four different outfits (black, white, black with white retroreflective strips, and black with white retroreflective strips to create biomotion) after dark. Pedestrians in the biomotion conditions were identified the most by drivers (93.8 %), whereas those wearing black clothing were identified the least (33.8 %). The same divergence was also noted for response distance, where biomotion enabled detection at the longest distance, and black clothing at the shortest distance (Wood et al., 2005).

1.4. Aim of the study

Numerous factors contribute to the occurrence of crashes involving pedestrians (Department for Transport, 2025; Yue et al., 2020). Yue et al. (2020) showed that a common scenario involves a vehicle traveling straight and a crossing pedestrian. In terms of crash causation patterns, distracted driving accounts for the largest proportion of pedestrian crashes (Yue et al., 2020). Secondary task engagement (e.g., using a mobile telephone) has increased in recent times, with their use as navigation devices in the vehicle. Currently, drivers in the UK are allowed to engage in hands-free mobile phone conversations as long as their view of the road and the traffic is not blocked and they do not hold the device (UK Government, n.d.). Cognitively demanding engagement in these non-visual/auditory tasks can reduce drivers' ability to detect peripheral objects. Based on the above studies, there is currently a gap in the research regarding the interaction between such cognitively demanding secondary tasks and drivers' hazard perception, including how these are influenced by different ambient lighting conditions. It is also not clear how drivers of different ages are affected by these factors, or if increasing pedestrian conspicuity can improve their detection by a cognitively distracted driver.

In addition to distraction-related crash patterns, reduced visibility has also emerged as a significant factor (Yue et al., 2020). Research investigating pedestrian crashes in the UK indicate that the likelihood of road traffic crashes increases after dark, particularly at crossings (e.g., Uttley & Fotios, 2017; Widodo et al., 2023). Building on these studies, the present study simulates the most common crash pattern while manipulating other relevant factors, such as distraction, ambient lighting, driver age, and zebra crossings. In our previous research using a driving simulator (Öztürk et al., 2023), we observed an increase in response time for the detection-response task with increased cognitive load, particularly among older drivers. The current study extends our previous research by examining drivers' yielding behaviour during pedestrian crossing events, where similar peripheral vision mechanisms are anticipated to be used. The current study also advances the area of research outlined in this section by incorporating multiple factors, typically examined in isolation into a unified experimental design. For example, there is only a limited body of research focusing on the effects of distraction on yielding behaviours of drivers (e.g., Krizsik & Sipos, 2024). Finally, the study introduces wearable LED bands as a novel and practical intervention to enhance conspicuity and assess its potential impact on driver behaviour in low-light conditions. By combining these variables within a single, high-fidelity driving simulator study, we aim to provide a more ecologically valid and comprehensive understanding of how these interacting factors influence drivers' real-time responses to pedestrian crossing events.

The study addressed the following research questions:

1. Does driver engagement in a cognitively demanding secondary task affect their behaviours, including the yielding rate and deceleration, during pedestrian crossing events?
2. To what extent does driver age, ambient lighting of the driving environment, and pedestrian position/conspicuity affect drivers' yielding behaviour?

3. Does the presence of zebra crossing affect drivers' yielding behaviour in the above conditions?

2. Method

2.1. Participants

The study was conducted with 42 drivers (23 younger and 19 older) as described in Table 1. All participants were required to have a valid driving license for at least three years, to drive regularly, to have driven at least 5000 miles in the last year (as judged by self-report), be between the ages of 21–25 years, or 60–75 years, and to have normal or corrected-to-normal vision.

2.2. Apparatus

The study was conducted using the University of Leeds Driving Simulator (UoLDS), an S-Type Jaguar encased by a 4 m spherical projection dome with a 300° projection angle and 8 degrees of freedom motion system (Fig. 1).

The experiment setting was a two-lane road in rural and village sections with a speed limit of 40 mph in the rural areas and 30 mph in the villages. All events occurred in the village sections, which consisted of straight roads. The rural sections consisted of straight and curved sections and were used to provide a break between villages. No other vehicles were present in the village sections, but oncoming traffic at a rate of six vehicles per km was present in the rural sections.

2.3. Experimental design

The study followed a mixed design approach, with within-participant factors of secondary task engagement (no task, 2-back task), pedestrian position (no pedestrian, standing pedestrian, walking pedestrian), presence of LED bands (with LED, without LED), presence of a zebra crossing (with crossing: marked, without crossing: unmarked), and lighting of the driving environment (daylight, after dark). Age group of participants (younger, older) was the only between-participants factor. Each of these conditions is outlined in more detail below.

2.4. Secondary task

The effect of cognitive distraction on drivers' interaction with pedestrians was investigated using a non-visual, auditory version of the n-back task (Mehler et al., 2011). Participants heard a list of numbers presented at regular intervals of every 2.25 s over the vehicle's speakers and were asked to repeat back the last-but-one number heard in the list (2-back). This was tape-recorded. Each section of the 2-back lasted approximately eight minutes (the full length of a village section).

2.5. Pedestrian position

To investigate how location and mobility of pedestrians affected detection by drivers, three levels of pedestrian position were implemented: no pedestrian (control condition), standing pedestrian (Fig. 2, lower yellow circle), and walking pedestrian (Fig. 2, upper yellow circle). A standing pedestrian was positioned one meter away from the roadside, with their head orientated towards the driver. However, they remained stationary as they were passed by the driver.

A walking pedestrian was positioned 8.5 m away from the roadside, which was visible to the driver. When the time-to-collision between the vehicle and the pedestrian was 5 s or the distance to the pedestrian was less than 50 m (whichever came first), the pedestrian started walking towards the zebra crossing at a speed of 1.5 m/s (or 5.4 km/h). Each walking pedestrian stopped at the same position as the standing pedestrians, looking towards the road. This interactive scenario allowed pedestrians to cross the road if the driver was within 50 m of their location and the vehicle's speed was less than 10 mph (16.09 km/h).

2.6. LED bands

To study the effect of conspicuity on drivers' response to pedestrians, half of the pedestrians were fitted with LED bands (see Fig. 3).

Table 1
Descriptive statistics.

		n	*Min.*	*Max.*	*Mdn*	*M*	*SD*
Age	Younger	23	21	25	22	22.39	1.20
	Older	19	60	73	64	65.37	4.32
Annual mileage	Younger	23	5000	18000	6000	7413.04	2851.05
	Older	19	7000	50000	10000	12184.21	9456.35
Male	Younger	11					
	Older	18					
Female	Younger	12					
	Older	1					

Fig. 1. The University of Leeds Driving Simulator.

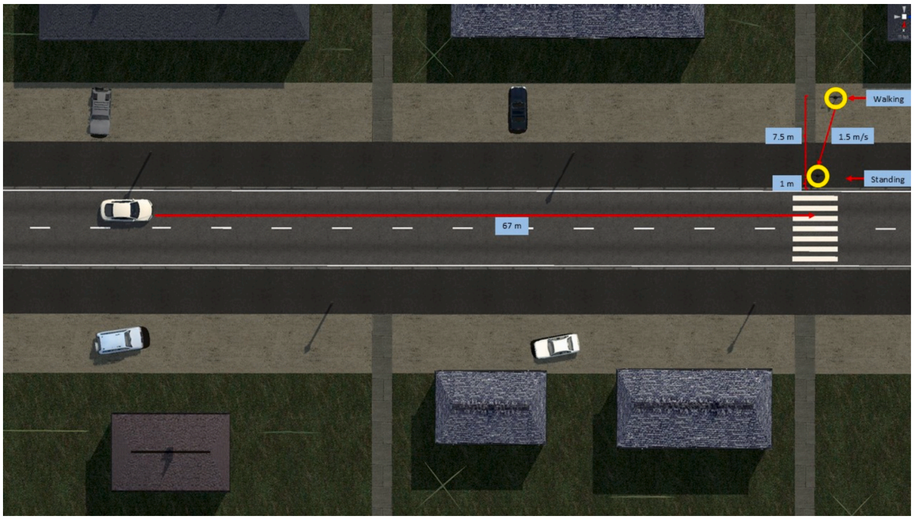

Fig. 2. Pedestrian positions (marked by the two circles) with respect to the zebra crossing.

Four LED bands were placed on each pedestrian (two on the wrists and two on the ankles) to mark biomotion for the walking pedestrians (Black et al., 2023). Pedestrians were outfitted in clothing of dark, subdued colours which is the least visible and most likely to go unnoticed in low light conditions (Black et al., 2023; Wood, 2023). Four different events were generated with pedestrian position and LED bands (standing pedestrian with/without LED bands and walking pedestrian with/without LED bands).

2.7. Presence of a zebra crossing

To understand if driver behaviour was influenced by zebra crossings, half of the pedestrian events occurred at locations with a zebra crossing, and the other half occurred at locations without a zebra crossing (see Fig. 2 for the location of a zebra crossing). In other words, the five events (no pedestrian, standing pedestrian with or without LED bands, and walking pedestrian with or without LED bands) occurred with equal frequency at locations with a zebra crossing and locations without a zebra crossing, resulting in ten different combinations.

2.8. Procedure

The study was approved by the School of Business, Environment and Social Services ethics committee at the University of Leeds (AREA FREC 2023–0446-395). Participants were recruited through the UoLDS participant database and social media platforms. They first completed an online survey to confirm their eligibility for the study. Eligible participants received an information sheet and a booking link to participate in the study.

On arrival at the experiment site at Virtuocity (https://uolds.leeds.ac.uk/facility/virtuocity/), University of Leeds, participants were informed about the experiment and completed an informed consent form. Participants then completed practice session of the 2-back task without driving and then an 8-kilometre practice drive in which they interacted with ten different events. Half of this drive

Fig. 3. Pedestrians with LED wrist and ankle bands.

was completed in the after dark condition. Participants also completed a short period of 2-back task while driving in both daylight and after dark conditions. An experimenter remained in the dome with the participants during the practice session, which lasted about 20 min. At the end of the practice period, verbal consent was obtained from each participant, stating that they had understood the tasks and had not experienced discomfort/motion sickness, after which the experimental session took place. During this session, participants completed two runs, with half of the participants randomly completing the daylight driving conditions first and the other half completing the after dark condition as their first drive.

Drivers were asked to drive as they normally would and were reminded of the designated speed limit. In terms of their interaction with pedestrians, they were reminded that pedestrians have the right of way at zebra crossings. No other instruction was given to manipulate their yielding behaviour.

Each of the two drives comprised a total of 40 crossing conditions, which were distributed evenly across the four village sections (see Fig. 4). The ten different crossing conditions outlined above were presented twice, resulting in 20 randomised trials for each drive. The twenty randomised trials were presented once without the 2-back task and once with the 2-back task for each drive (40 times in total). The distance between any two events was 500 m. A single experimental drive was about 25 km long, lasting about 35 mins to complete.

There was a 5-minute break between the two drives. After each driving session (daylight and after dark driving), participants completed the Traffic Climate Scale to assess their perceptions of the simulated driving environment (Üzümcüoğlu et al., 2020). At the end of the second experimental drive, participants completed the final part of the experiment, which included self-report measures of LED acceptance (see Öztürk et al., 2024 for the results). The entire experiment took approximately two hours, for which participants received £40 (Fig. 5).

In summary, each participant engaged in two driving sessions, one conducted during conditions resembling daylight and the other after dark, thereby experiencing all combinations of within-subject variables throughout the experiment. The sequence of ambient lighting and secondary task conditions was counterbalanced among participants to mitigate order effects, and all event combinations were randomised both within and across driving sessions to prevent sequence bias. This methodological approach ensured that each participant encountered an equivalent number and type of pedestrian scenarios under each experimental condition, albeit not necessarily in the same sequence.

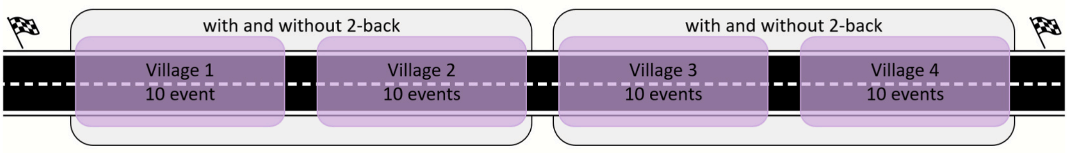

Fig. 4. Single-drive event structure.

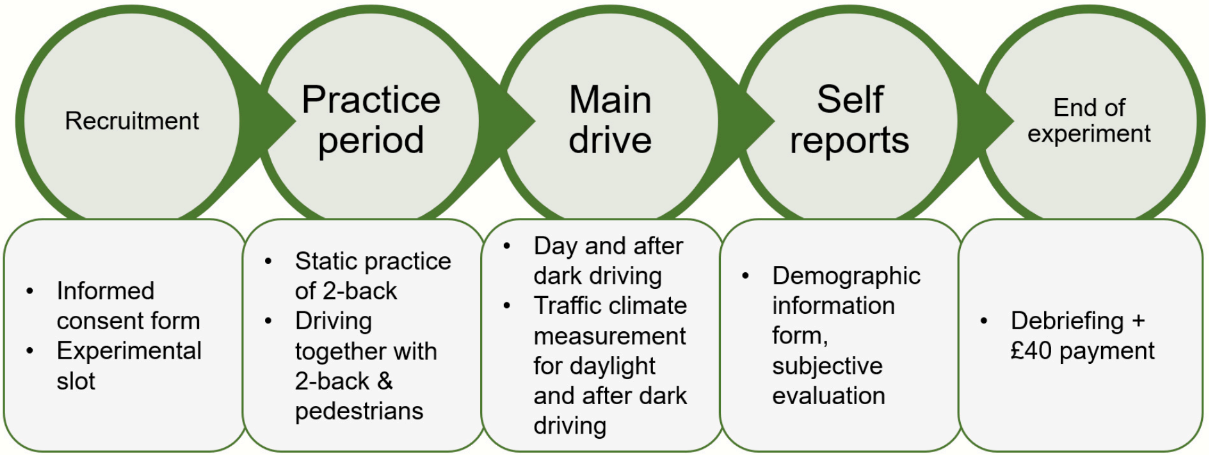

Fig. 5. Study procedure.

2.9. Data analyses

The analysis used the objective data. Given the aims of the study, only events involving driver response to pedestrians are included. A total of 2592 pedestrian events were recorded. Data were extracted using MATLAB R2020a. Analyses were conducted with Jamovi 2.6.44 (The Jamovi Project, 2023; R Core Team, 2022), testing with General Analyses for the Linear Model in Jamovi (GAMLj, Gallucci, 2019). In the absence of suitable data from previous studies, the sample size was established based on previous relevant driving simulator studies (e.g., Bobermin et al., 2021; Papantoniou et al., 2017; Soares et al., 2020), and consideration of the between- and within-subject variables of the study.

For 2-back performance, two descriptive metrics were calculated: response rate (the percentage of responses provided by the participant, regardless of accuracy) and the percentage of correct responses. The performance was analysed using a 2 (age: younger vs older) and a 2 (ambient lighting: daylight vs after dark) mixed ANOVA (Section 3.1).

For the objective driving simulator data, a Generalised Linear Mixed Effects Model (GLMM, Section 3.2.1) with a binary response (0 = the vehicle continued, 1 = the driver yielded to the pedestrian – the pedestrian crossed the road) was used to investigate what factors influenced drivers' decision to yield to a pedestrian (e.g., Kalantari et al., 2023). Following the initial GLMM model, a separate mixed-effects models (Section 3.2.2) was conducted to analyse the variables influencing average deceleration (m/s^2; in negative values: the lower the value, the greater the deceleration rate). This was calculated from 67 m before the pedestrian event, and was based on the visibility of pedestrians in the driving scene, also allowing a five-second period for the walking pedestrian to reach the edge of the road (e.g., Ābele et al., 2018; Bella & Silvestri, 2015; Calvi et al., 2020; Kalantari et al., 2023).

Among the 2592 pedestrian events, drivers yielded, or stopped for the pedestrian, in 875 instances, resulting in an overall yielding rate of 33.8 %. Of the 875 yielding events, 93.9 % occurred in the presence of a zebra crossing (822 instances), whereas only 6.1 % took place in the absence of such infrastructure (53 instances). During the initial GLMM analysis, the variable exhibited extremely large coefficients, which could potentially lead to inflated standard errors. As a result, scenarios without a zebra crossing were omitted from subsequent analyses, and the analyses were conducted exclusively on scenarios where a zebra crossing was present.

Each statistical model employed the subject ID for random coefficients and included the main and two-way interaction effects of variables. To address overdispersion observed in the binomial model (initial χ^2/df = 2.785), an observation-level random effect (OLRE, Harrison, 2014) was added, resulting in improved model fit and an acceptable dispersion ratio (χ^2/df = 0.361). Only the main effects and the two-way interaction effects were entered into the models due to the sample size and the number of interactions. Detailed figures on each significant effect, including confidence intervals and random effects, are presented in the appendices for the GLMM (Appendix A) and the LMM (Appendix B).

Table 2
Descriptives on 2-back performance.

	Age	Mean	Median	SD	Minimum	Maximum
Response rate (%) – Daylight	Younger	84.33	85.79	15.97	27.71	100.00
	Older	73.86	73.80	16.52	29.95	97.42
Response rate (%) – After dark	Younger	86.02	85.43	14.24	31.89	100.00
	Older	77.28	78.09	13.89	41.12	100.00
Percentage of correct response – Daylight	Younger	55.07	57.10	25.99	10.12	87.69
	Older	54.68	50.25	20.53	20.72	98.40
Percentage of correct response – After dark	Younger	55.57	59.65	25.10	10.91	89.40
	Older	56.08	61.52	18.53	24.10	92.25

3. Results

3.1. 2-back performance

The analysis of 2-back performance (Table 2) showed that younger drivers exhibited a slightly higher response rate compared to older drivers ($F(1, 40) = 4.51$, $p = 0.004$, $\eta_p^2 = 0.10$). The effects of ambient lighting ($F(1, 40) = 3.86$, $p = 0.056$) and the interaction between ambient lighting and age ($F(1, 40) = 0.44$, $p = 0.510$) were not statistically significant. Furthermore, the percentage of correct responses was similar across both age groups and ambient lighting conditions, with non-significant effects observed for age ($F(1, 40) = 0.00$, $p = 0.992$), ambient lighting ($F(1, 40) = 0.15$, $p = 0.698$), and their interaction ($F(1, 40) = 0.03$, $p = 0.854$).

3.2. Driver behaviour

To examine the effect of the different factors on drivers' response to pedestrians, we assessed yielding behaviour (likelihood of yielding), and then assessed drivers' average deceleration.

3.2.1. Yielding behaviour

Table 3 shows the factors impacting the outcome of the interaction, as determined through the GLMM for the conditions when a zebra crossing was present. Significant main effects were observed for pedestrian position and presence of the secondary task. Furthermore, two-way interactions (age by pedestrian position, ambient lighting by pedestrian position, and pedestrian position by secondary task) were all significant.

Drivers gave way more when a standing pedestrian was located on the roadside (prob. = 0.993) than when a pedestrian was walking (prob. = 0.341, $p_{\text{bonf}} < 0.001$). As for the main effect of secondary task, the pairwise comparison between the presence (prob. = 0.877) and absence (prob. = 0.912) of the 2-back task did not yield a statistically significant result ($p_{\text{bonf}} = 0.142$).

The interaction between age group and pedestrian position (Fig. 6), reflected that older drivers were much less likely to stop for walking pedestrians (prob. = 0.076) than standing pedestrians (prob. = 0.987, $p_{\text{bonf}} < 0.001$). Younger drivers were also significantly more likely to standing pedestrians (prob. = 0.996) than walking pedestrians (prob. = 0.764, $p_{\text{bonf}} < 0.001$). Therefore, the significant interaction indicates that the comparison of standing and walking pedestrians was greater for older than younger drivers.

Regarding the interaction effects of ambient lighting and pedestrian position (Fig. 7), drivers demonstrated a higher likelihood of yielding to standing pedestrians, both during daylight (prob. = 0.995) and after dark (prob. = 0.990), compared to pedestrians who were walking, either during daylight (prob. = 0.286, $p_{\text{bonf}} < 0.001$) or after dark (prob = 0.399, $p_{\text{bonf}} < 0.001$).

Table 3
Results of the GLMM on the likelihood of yielding.

				95 % Confidence Intervals				
Names	Effect	Estimate	SE	Lower	Upper	Exp(B)	z	p
(Intercept)	(Intercept)	6.618	1.252	64.307	8704.0	748.129	5.286	<.001
Age group	Older (1) – Younger (0)	−1.954	1.610	0.006	3.324	0.142	−1.214	0.225
Ambient lighting	After dark (1) – Daylight (0)	−1.080	0.579	0.109	1.057	0.340	−1.865	0.062
LED	With LED (1) – Without LED (0)	0.160	0.588	0.371	3.718	1.174	0.272	0.785
Pedestrian position	**Walking (1) – Standing (0)**	**−5.519**	**0.665**	**0.001**	**0.015**	**0.004**	**−8.299**	**<.001**
Secondary task	**2-back task (1) – No task (0)**	**−1.232**	**0.571**	**0.095**	**0.894**	**0.292**	**−2.156**	**0.031**
Age group by ambient lighting	(Older – Younger) * (After dark – Daylight)	0.167	0.481	0.460	3.033	1.181	0.346	0.729
Age group by LED	(Older – Younger) * (With LED – Without LED)	0.543	0.473	0.681	4.346	1.721	1.149	0.251
Ambient lighting by LED	(After dark – Daylight) * (With LED – Without LED)	0.594	0.472	0.718	4.567	1.811	1.258	0.208
Age group by pedestrian position	**(Older – Younger) * (Walking – Standing)**	**−2.382**	**0.735**	**0.022**	**0.390**	**0.092**	**−3.242**	**0.001**
Ambient lighting by pedestrian position	**(After dark – Daylight) * (Walking – Standing)**	**1.211**	**0.490**	**1.285**	**8.769**	**3.356**	**2.471**	**0.013**
LED by pedestrian position	(With LED – Without LED) * (Walking – Standing)	−0.482	0.487	0.238	1.605	0.618	−0.989	0.323
Age group by secondary task	(Older – Younger) * (2-back task – No task)	0.630	0.481	0.732	4.818	1.878	1.311	0.190
Ambient lighting by secondary task	(After dark – Daylight) * (2-back task – No task)	−0.014	0.475	0.388	2.503	0.986	−0.029	0.977
LED by secondary task	(With LED – Without LED) * (2-back task – No task)	−0.334	0.476	0.282	1.820	0.716	−0.702	0.483
Pedestrian position by secondary task	**(Walking – Standing) * (2-back task – No task)**	**1.449**	**0.499**	**1.601**	**11.324**	**4.258**	**2.904**	**0.004**
AIC = 657.3, BIC = 750.3, LogLikel = -310.6, Residual df = 1278, ICC = 0.854								

Note: Significant effects are shown in bold.

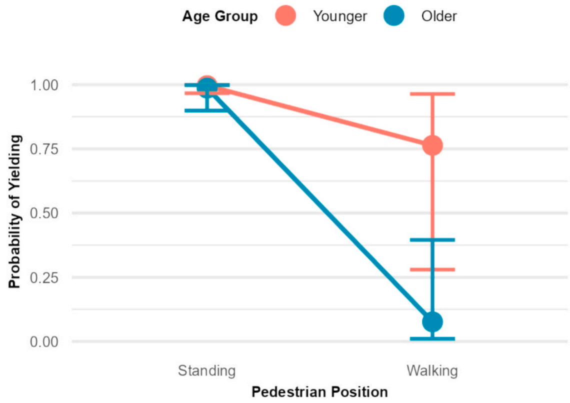

Fig. 6. The probability of yielding as a function of pedestrian position and age group.

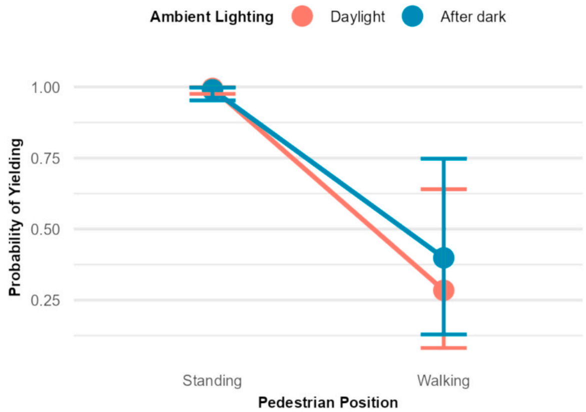

Fig. 7. The probability of yielding as a function of pedestrian position and ambient lighting.

Regarding the interaction between pedestrian position and secondary task (Fig. 8), drivers exhibited the highest likelihood of yielding to standing pedestrians when the 2-back task was absent (prob. = 0.996). This probability slightly decreased for standing pedestrians when the 2-back task was present (prob. = 0.988, $p_{\text{bonf}} = 0.034$) and further declined for walking pedestrians both in the presence of the 2-back task (prob. = 0.382, $p_{\text{bonf}} < 0.001$) and in its absence (prob. = 0.302, $p_{\text{bonf}} < 0.001$).

Among zebra crossing conditions, pedestrian position had more substantial effects on the probability of yielding than factors such as age, LED bands, and the secondary task. To explore the effects of these variables, we performed additional analyses of the drivers' behaviours, considering the average deceleration rate while yielding (Table 4).

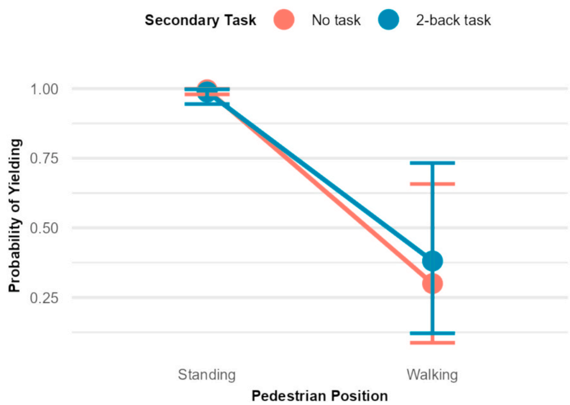

Fig. 8. The probability of yielding as a function of pedestrian position and secondary task.

Table 4
Results of the LMM on average deceleration.

Names	Effect	Omnibus Tests			Estimate	SE	95 % Confidence Interval		df	t	p
		F	*df*(1, res)	*p*			Lower	Upper			
(Intercept)	(Intercept)				−1.787	0.147	−2.076	−1.497	65.970	−12.123	<.001
Age group	Older (1) – Younger (0)	1.776	38.662	0.190	0.502	0.204	0.101	0.903	54.189	2.457	0.017
Ambient lighting	After dark (1) – Daylight (0)	1.196	773.966	0.274	−0.067	0.101	−0.265	0.131	773.751	−0.663	0.507
LED	**With LED (1) − Without LED (0)**	**8.193**	**767.401**	**0.004**	**0.190**	**0.098**	**−0.003**	**0.382**	**766.770**	**1.932**	**0.054**
Pedestrian position	**Walking (1) – Standing (0)**	**72.010**	**791.223**	**0<.001**	**−0.345**	**0.112**	**−0.565**	**−0.124**	**774.722**	**−3.069**	**0.002**
Secondary task	**2-back task (1) − No task (0)**	**14.110**	**768.099**	**0<.001**	**−0.269**	**0.099**	**−0.463**	**−0.074**	**768.175**	**−2.709**	**0.007**
Age group by ambient lighting	**(Older − Younger) * (After dark − Daylight)**	**6.670**	**774.411**	**0.010**	**−0.259**	**0.100**	**−0.456**	**−0.062**	**774.411**	**−2.583**	**0.010**
Age group by LED	(Older − Younger) * (With LED − Without LED)	0.435	767.495	0.510	−0.065	0.098	−0.258	0.128	767.495	−0.660	0.510
Ambient lighting by LED	(After dark − Daylight) * (With LED − Without LED)	3.359	767.864	0.067	0.175	0.095	−0.012	0.362	767.864	1.833	0.067
Age group by pedestrian position	**(Older − Younger) * (Walking − Standing)**	**4.532**	**791.087**	**0.034**	**−0.263**	**0.123**	**−0.505**	**−0.020**	**791.087**	**−2.129**	**0.034**
Ambient lighting by pedestrian position	(After dark − Daylight) * (Walking − Standing)	2.276	770.112	0.132	0.159	0.105	−0.048	0.365	770.112	1.509	0.132
LED by pedestrian position	**(With LED − Without LED) * (Walking − Standing)**	**7.127**	**767.792**	**0.008**	**−0.278**	**0.104**	**−0.483**	**−0.074**	**767.792**	**−2.670**	**0.008**
Age group by secondary task	(Older − Younger) * (2-back task − No task)	0.729	768.454	0.393	0.084	0.099	−0.109	0.278	768.454	0.854	0.393
Ambient lighting by secondary task	(After dark − Daylight) * (2-back task − No task)	0.361	767.867	0.548	−0.057	0.095	−0.244	0.130	767.867	−0.601	0.548
LED by secondary task	(With LED − Without LED) * (2-back task − No task)	0.885	767.305	0.347	0.090	0.095	−0.097	0.276	767.305	0.941	0.347
Pedestrian position by secondary task	(Walking − Standing) * (2-back task − No task)	0.062	767.549	0.804	0.026	0.104	−0.179	0.231	767.549	0.249	0.804

Marginal R^2 = 0.142, Conditional R^2 = 0.484, AIC = 1871.426, BIC = 1956.237, LogLikel = -917.713, ICC = 0.399.

Note: Significant effects are shown in bold.

3.2.2. Average deceleration

A mixed-effects model was employed to investigate the impact of our variables on drivers' deceleration rate on approach to the zebra crossing (Table 4). Results showed that the LED bands, pedestrian position, and the secondary task had significant main effects on average deceleration. Moreover, significant two-way interactions were seen between age group and ambient lighting, age group and pedestrian position, and LED bands and pedestrian position.

The presence of LED bands resulted in less severe decelerations by drivers ($EMM = -1.804$) compared to when LED bands were absent ($EMM = -1.954$, $p_{bonf} = 0.004$). The deceleration rate was also lower when yielding for standing pedestrians ($EMM = -1.617$) than for walking pedestrians ($EMM = -2.140$, $p_{bonf} < 0.001$). The deceleration rate was also lower in the absence of the 2-back task ($EMM = -1.780$) in comparison to the presence of 2-back task ($EMM = -1.977$, $p_{bonf} < 0.001$).

Based on the post hoc comparisons of age group by ambient lighting interaction, no significant differences were observed in any of the pairwise comparisons. The interaction between age group and pedestrian position (Fig. 9) revealed that older drivers decelerated more severely when encountering walking pedestrians ($EMM = -2.200$) than standing pedestrians ($EMM = -1.426$, $p_{bonf} < 0.001$).

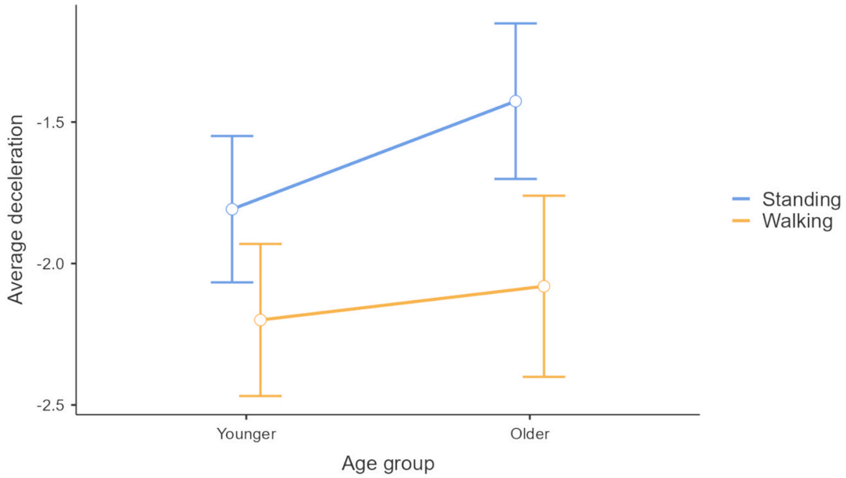

Fig. 9. Average deceleration (m/s^2) by age group by pedestrian position.

Similarly, younger drivers exhibited a higher deceleration rate for walking pedestrians ($EMM = -2.081$) compared to both their own ($EMM = -1.808$, $p_{bonf} < 0.001$) and older drivers' ($p_{bonf} = 0.001$) deceleration rates for standing pedestrians.

The interaction between LED bands and pedestrian position (Fig. 10) revealed that the highest deceleration was applied in response to walking pedestrians, whether ($EMM = -2.135$) or not ($EMM = -2.146$) they were wearing LED bands. The rate of deceleration exhibited a gradual decrease for standing pedestrians without LED bands ($EMM = -1.762$) and subsequently for those with LED bands ($EMM = -1.473$, $p_{\mathrm{bonf}} < 0.001$).

4. Discussion

In this driving simulator study, we investigated how two groups of drivers (younger and older) responded to a set of walking and standing pedestrians when approaching them in a simulated urban environment while being cognitively loaded or not. The effect of ambient lighting (daylight, after dark) and the presence of zebra crossing on this response was also studied. To establish if response was influenced by additional visual aids, one set of pedestrians were also equipped with LED bands.

4.1. Discussion of the main findings

Regarding the 2-back performance, results showed that although younger drivers demonstrated higher levels of engagement compared to older drivers, younger and older drivers did not exhibit significant differences in the correct response rate. The average percentage of correct responses provided by drivers in this study was also lower than that seen in previous studies (e.g., Goodridge et al., 2024; Öztürk et al., 2023). This may be due to length of the 2-back task used in the current study (8 min), which may have induced mental fatigue (Dallaway et al., 2022). Furthermore, similar to Goodridge et al. (2024), substantial individual variations were observed among both younger and older drivers' response rate and percentage of correct response. Further research is warranted to examine the effects of 2-back task duration on performance in future studies.

Regarding drivers' reactions to pedestrian scenarios, the overall yielding rate was 33.8 %. This is similar to the findings of observational studies (Bertulis & Dulaski, 2014; O'Toole et al., 2025; Rosenbloom et al., 2006; Schneider et al., 2018; Sucha et al., 2017), indicating low yielding. Contrary to our expectations, both age and the 2-back task showed a limited influence on drivers' yielding decisions, while environmental factors (i.e., the presence of a zebra crossing, ambient lighting, and LED bands) played a stronger role in determining the outcome, which is in line with previous experimental (e.g., Kalantari et al., 2023; Madigan et al., 2023) and real-world (Anciaes et al., 2020) studies. The presence of a zebra crossing was the strongest predictor of yielding behaviour, which is in line with current traffic regulations in the UK (The Highway Code, 2023) and previous observational (e.g., Mitman et al., 2008) and simulation (Obeid et al., 2017) studies.

As for the age-related differences, both groups exhibited similar yielding behaviour towards standing pedestrians. However, when interacting with walking pedestrians, younger drivers displayed a greater tendency to yield and exhibited softer yielding behaviours (i.e., lower deceleration rate). As pedestrians approached the crossing, younger drivers appeared to be more proactive in yielding. This is in line with previous studies, showing age-related differences in hazard perception skills (Folli & Bennett, 2023), crash involvement (Lee & Abdel-Aty, 2005), and pedestrian detection (Wood et al., 2005; 2014). Previous research (McGwin et al., 2000) has demonstrated that among older drivers, aged 55 to 85, diminished visual acuity and contrast sensitivity exacerbate driving difficulties, even when age is controlled for. While all participants were noted to have normal or corrected-to-normal vision, older drivers reported greater difficulty in detecting pedestrians compared to their younger counterparts in this study (Öztürk et al., 2024). This is also reflected in their yielding behaviour towards walking pedestrians. This observation may indicate that older drivers have delayed and

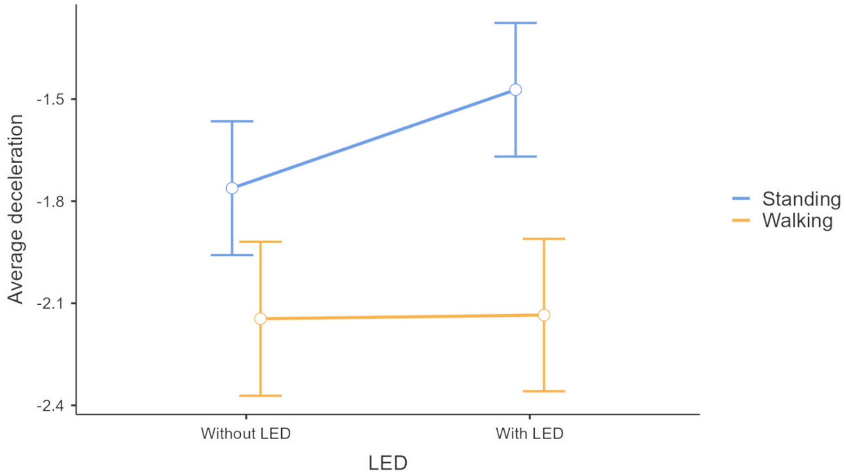

Fig. 10. Average deceleration (m/s^2) by LED bands by pedestrian position.

more abrupt response to pedestrians, potentially due to deteriorated useful field of view (Anstey et al., 2005; Rogé & Pébayle, 2009), slower reactions (e.g., Singh & Kathuria, 2021), and failure to detect pedestrians earlier (e.g., Wood et al., 2014).

Consistent with previous research emphasising narrower peripheral detection (e.g., Choudhary & Velaga, 2017; Harbluk et al., 2007; Savage et al., 2019) and delayed detection of pedestrians and slower response (Baldo et al., 2020) with increased cognitive load, drivers' engagement in a cognitively demanding task resulted in a small but significant reduction in their likelihood of yielding to standing pedestrians and increased deceleration rate when yielding. These findings support Anttila and Luoma (2005), who concluded that increased cognitive load may be associated with "inappropriate behaviour towards vulnerable road users". In our study, this inappropriate behaviour was evidenced by a reduction in yielding frequency as well as more pronounced (i.e., harsher) deceleration.

As for the effects of pedestrian position, in line with the findings of Sucha et al. (2017), drivers were more likely to yield to pedestrians standing near the roadside. Interestingly, no interaction effect was observed for LED bands and walking (i.e., biomotion). This may be explained by the controlled study design, where pedestrians were visible from a distance and presented no immediate hazard to the drivers. Since pedestrians only began crossing when vehicles had already decelerated to a predetermined level, drivers faced a minimal need to execute abrupt or forced yields or uncertainty for walking pedestrians. Furthermore, in line with Schneider et al. (2017), drivers were less likely to engage in harsh braking for standing pedestrians, likely because they were visible and stationary by the roadside well before the drivers' arrival. However, due to increased workload in limited ambient lighting and urban driving (Yared & Patterson, 2020), drivers may have had difficulty responding to pedestrians without additional visual cues in low-light situations.

Examining the changes in drivers' yielding and braking behaviour revealed that the use of LED bands does not impact drivers' decision to yield but rather renders this behaviour smoother. On other words, the introduction of LED bands on pedestrians appeared to have a mitigating effect on some of the challenges posed by limited ambient lighting and increased cognitive load. Drivers commonly reported increased visibility of pedestrians with LED bands at after dark conditions and showed greater acceptance of the bands (Öztürk et al., 2024). Furthermore, for standing pedestrians, the presence of LED bands led to reduced average deceleration, implying that drivers were able to respond to pedestrians more smoothly and gradually. These findings corroborate previous research that suggests pedestrians with LED bands are detected earlier (e.g., Black et al., 2023; Wood et al., 2005), which leads to a less abrupt response, possibly because the salient cue of the LEDs provides drivers with additional time/distance to respond. This underscores the potential of increased conspicuity to enhance pedestrian safety, particularly in challenging driving conditions.

4.2. Limitations and recommendations for future research and practice

Regarding the limitations and further improvements in future studies, this experiment was conducted in a simulated driving environment, which, although very immersive, could also pose a limitation regarding the realism of the pedestrians, but especially the lighting provided in the virtual environment. Therefore, validation of response to LEDs in real-world driving scenarios is warranted (e.g., Wood, 2023). Considering that driver behaviour is known to be affected by circadian rhythms (e.g., Chipman & Jin, 2009) and other lifestyle patterns governed by the time of day (e.g., Papadakaki et al., 2008), future studies may consider data collection at different times of the day, to accurately represent day and after dark conditions.

The study exhibits a gender imbalance, particularly among older participants. We believe that the inclusion of the random effect in our models partially accounts for any potential influence of gender on the findings, as it captures individual variability across the repeated measures. However, existing research also indicates that older female drivers tend to exhibit lower confidence in their driving abilities and are more likely to engage in self-regulatory behaviours, such as avoiding driving under risky conditions, including after dark driving (Charlton et al., 2006). Due to this, despite our efforts for recruitment, older female drivers may have demonstrated reluctance to participate in our study. Additionally, driving experience represents another variable that warrants investigation in future research. As we established a minimum driving experience requirement for both younger and older participants, the anticipated effect is minimal. However, future studies with larger sample sizes could explore various age, gender, and experience levels to investigate further interaction effects.

While our study concentrated on several critical factors, it is important to consider additional elements at the different levels of crash causation (Yue et al., 2020) such as drivers' emotional state (e.g., Steinhauser et al., 2018), drowsiness (Soares et al., 2020), and environmental factors like the presence of stores and parks (Li et al., 2025). These variables represent important avenues for future investigation, particularly as they may interact with the mechanisms examined in the current study. Investigating how these additional factors influence drivers' yielding behaviour would provide a more comprehensive understanding of the underlying behavioural processes and could contribute to the refinement of safety interventions.

4.3. Implications

The study presents several significant implications and contributions. A primary contribution is the integration of multiple critical variables, driver age, cognitive distraction, ambient lighting, pedestrian behaviour, zebra crossings, and LED-based conspicuity aids, into a single experimental framework. This study is among the first to assess their combined and interaction effects on drivers' yielding and braking behaviour in realistic pedestrian scenarios. This multifactorial approach mirrors the complex and dynamic nature of real-world driving environments, facilitating a more comprehensive understanding of pedestrian-driver interactions. Additionally, the study directly compares two high-risk driver groups. By systematically evaluating their performance under varying levels of cognitive load and ambient lighting, the study provides comparative insights into age-specific vulnerabilities, which can inform the development of targeted safety measures.

In terms of the value of this work for policy recommendations, the results and methodology of the current study could be used to provide evidence-based guidance for infrastructure design and policy interventions aimed at enhancing pedestrian safety through improved visibility and hazard awareness. They could also inform the development of driver training programmes to increase awareness of vulnerable road users and hazard perception skills (e.g., Pradhan et al., 2009; Rogé et al., 2014). More empirical intervention studies can be conducted to examine changes in driver behaviour as awareness of vulnerable road users increases. One evident implication of this study is the significance of marked pedestrian crossings in influencing driver behaviour. Our findings indicate that, in the majority of instances, drivers yielded in the presence of a zebra crossing. This underscores the importance of investing in well-marked and visible pedestrian infrastructure, particularly in areas with high pedestrian activity, as a fundamental road safety measure.

An innovative aspect of this study is the use of wearable LED bands to enhance pedestrian conspicuity. Unlike retroreflective clothing or standard lighting interventions, LED bands offer a portable, low-cost solution with high conspicuity across a wide range of ambient lighting conditions. While prior research has demonstrated their effectiveness in detection tasks in controlled on-road studies (e.g., Black et al., 2023), this study is, to our knowledge, the first to assess their impact on behavioural response in a driving simulator. The findings suggest that although LED bands did not significantly increase the likelihood of yielding, they resulted in smoother deceleration, potentially indicating earlier detection and more controlled responses for standing pedestrians. This suggests that LED bands may offer a potential safety benefit, albeit lower than anticipated, especially for walking pedestrians. Future research could benefit from gathering pedestrians and other vulnerable road users' perspectives (e.g., Fylan et al., 2020) to effectively demonstrate the advantages of LED bands and to refine related policy for their use.

Finally, this study shows the significant impact of different ambient lighting and environmental conditions on drivers' response to pedestrians. In a recent review of cycling and road lighting, Vidal-Tortosa and Lovelace (2024) stated the need for more empirical studies to find the optimal lighting levels for visibility of vulnerable road users. Building on this suggestion, future studies may also benefit from assessing how LED bands or (or other alternatives such as high visibility vests that increase conspicuity; Wood et al., 2022) affect drivers' response to and detection of vulnerable road users.

CRediT authorship contribution statement

İbrahim Öztürk: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anthony Horrobin:** Software, Data curation. **Jorge Garcia de Pedro:** Software, Data curation. **Kumsal İpek Oker:** Formal analysis, Data curation. **Richard Rowe:** Writing – review & editing, Methodology, Conceptualization. **Steve Fotios:** Writing – review & editing, Methodology, Conceptualization. **Natasha Merat:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Cooperation on Theories and Concepts in Traffic Safety (ICTCT) conference in the Netherlands. The researchers express their gratitude towards Courtney Goodridge, Rafael Cirino Goncalves, Yee Thung Lee, Burcu Arslan, and the University of Leeds Driving Simulator team for their invaluable assistance.

Data access statement

The data that support the findings of this study are available on request from the corresponding author (I.O., i.ozturk@leeds.ac.uk).

Appendix A:. Additional significant effect plots for the GLMM results

Fig. A1. The probability of yielding as a function of pedestrian position. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

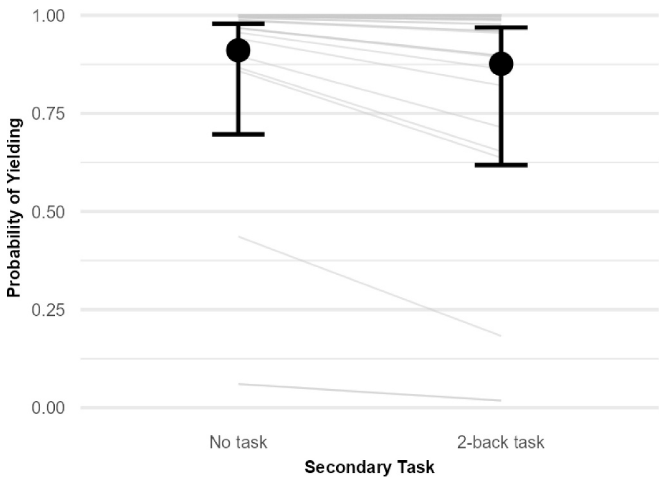

Fig. A2. The probability of yielding as a function of secondary task. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

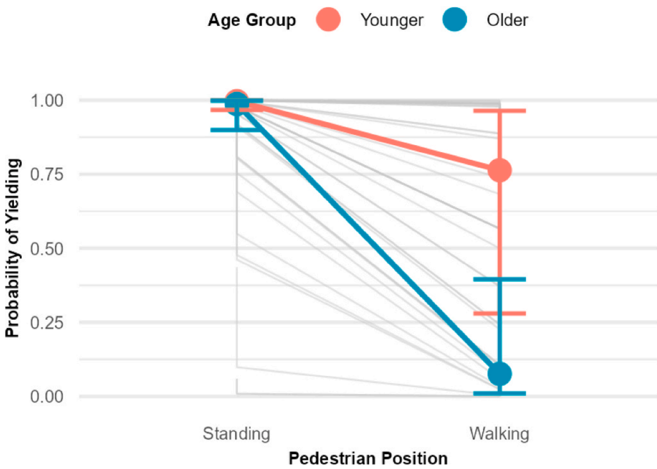

Fig. A3. The probability of yielding as a function of pedestrian position and age group. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

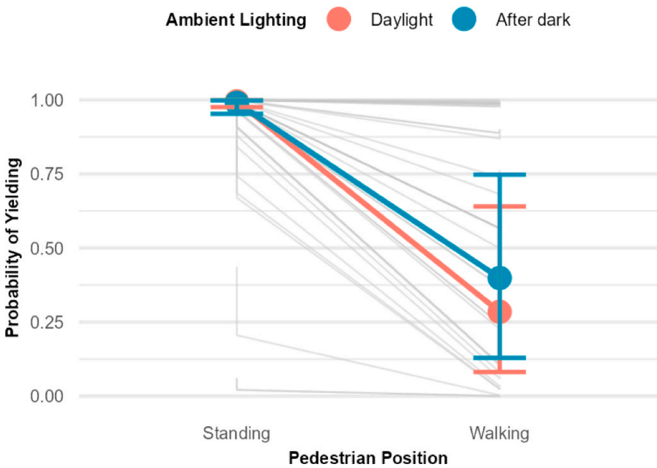

Fig. A4. The probability of yielding as a function of pedestrian position and ambient lighting. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

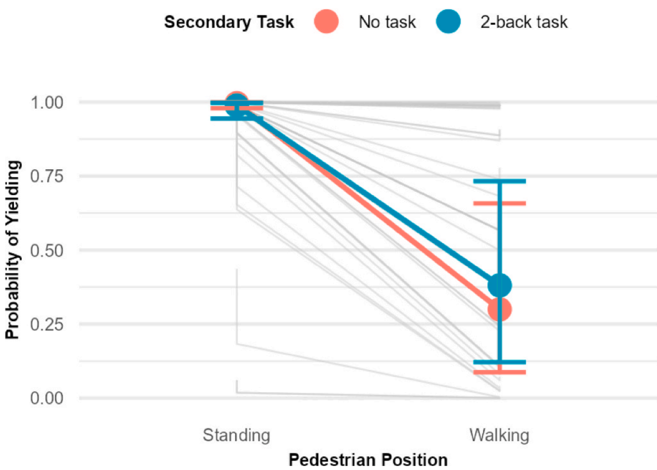

Fig. A5. The probability of yielding as a function of pedestrian position and secondary task. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

Appendix B:. Additional significant effect plots for the LMM results

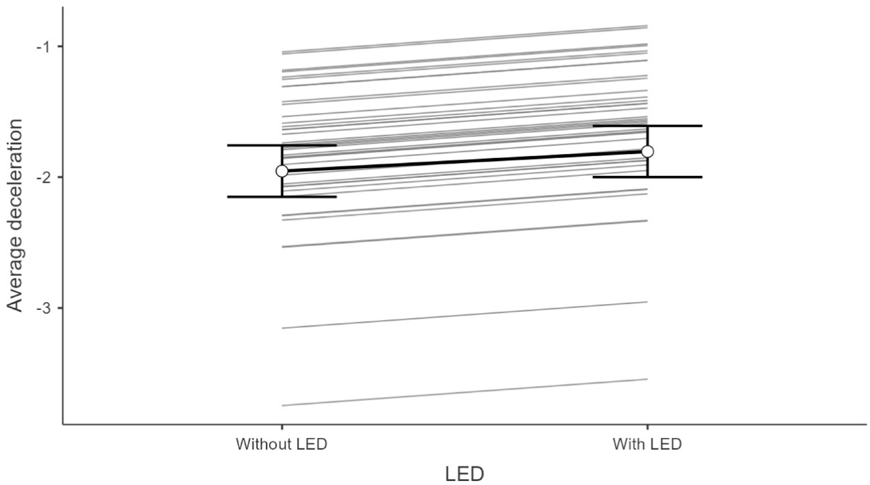

Fig. B1. Average deceleration (m/s^2) by LED bands. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

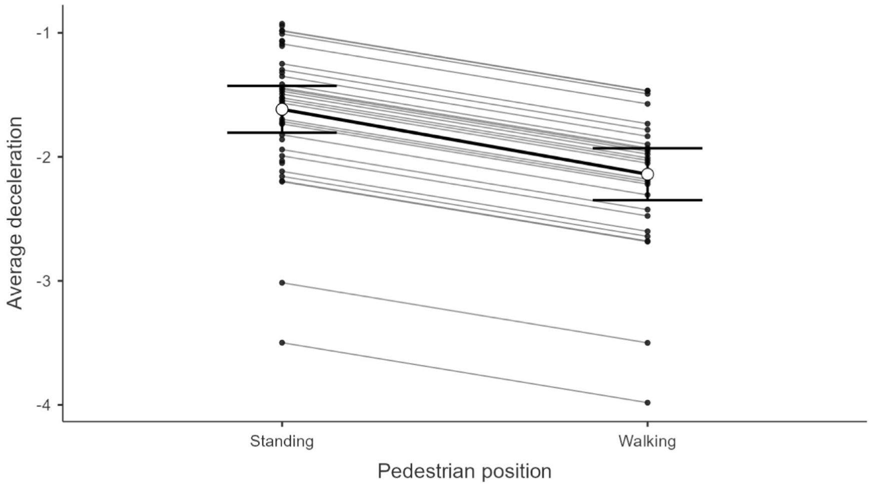

Fig. B2. Average deceleration (m/s^2) by pedestrian position. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

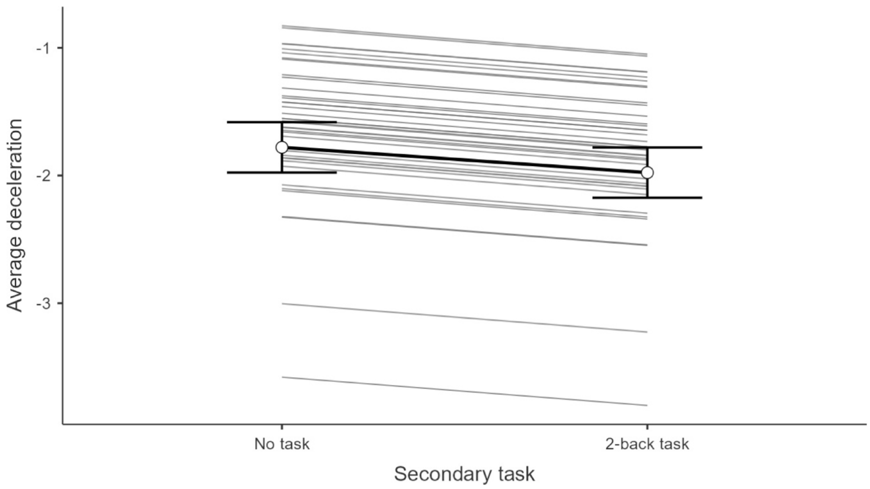

Fig. B3. Average deceleration (m/s^2) by secondary task. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

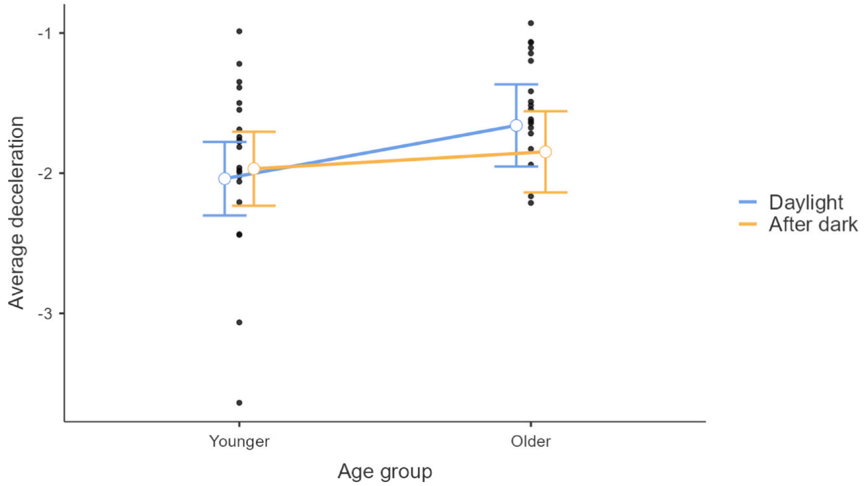

Fig. B4. Average deceleration (m/s^2) by age group by ambient lighting. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

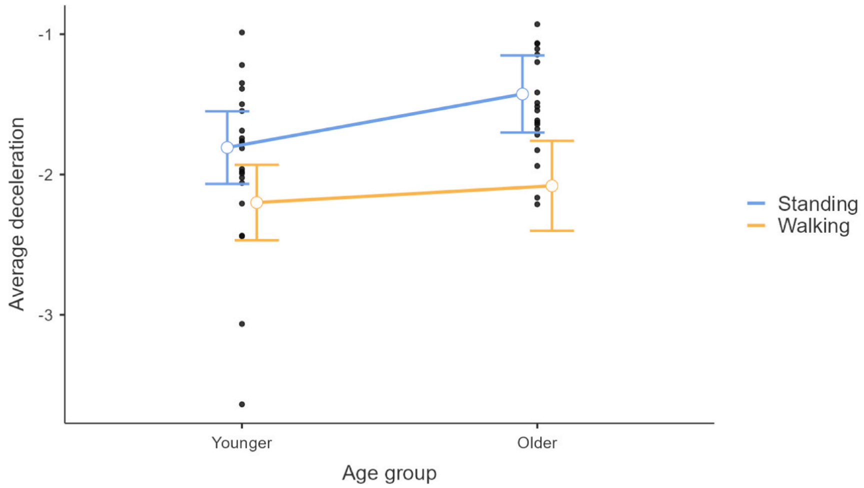

Fig. B5. Average deceleration (m/s^2) by age group by pedestrian position. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

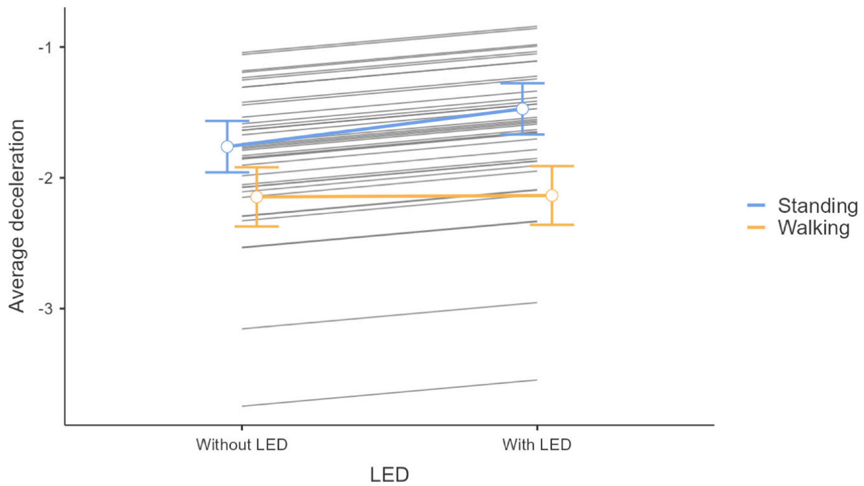

Fig. B6. Average deceleration (m/s^2) by LED bands by pedestrian position. The thick lines indicate the marginal means, while the thin (grey) lines represent the random effects for each subject.

Data availability

Data will be made available on request.

References

Ābele, L., Haustein, S., & Møller, M. (2018). Young drivers' perception of adult and child pedestrians in potential street-crossing situations. *Accident Analysis & Prevention, 118*, 263–268. https://doi.org/10.1016/j.aap.2018.03.027

Al-Kaisy, A., Miyake, G. T., Staszcuk, J., & Scharf, D. (2018). Motorists' voluntary yielding of right of way at uncontrolled midblock crosswalks with rectangular rapid flashing beacons. *Journal of Transportation Safety & Security, 10*(4), 303–317. https://doi.org/10.1080/19439962.2016.1267827

Amado, H., Ferreira, S., Tavares, J. P., Ribeiro, P., & Freitas, E. (2020). Pedestrian–vehicle interaction at unsignalized crosswalks: A systematic review. *Sustainability, 12*(7), 2805. https://doi.org/10.3390/su12072805

Anciaes, P., Di Guardo, G., & Jones, P. (2020). Factors explaining driver yielding behaviour towards pedestrians at courtesy crossings. *Transportation Research Part F: Traffic Psychology and Behaviour, 73*, 453–469. https://doi.org/10.1016/j.trf.2020.07.006

Anderson, J. C., Kothuri, S., Monsere, C., & Hurwitz, D. (2022). Systemic opportunities to improve older pedestrian safety: Merging crash data analysis and a stakeholder workshop. *Transportation Research Record: Journal of the Transportation Research Board, 2676*(10), 351–360. https://doi.org/10.1177/03611981221089312

Anstey, K. J., Wood, J., Lord, S., & Walker, J. G. (2005). Cognitive, sensory and physical factors enabling driving safety in older adults. *Clinical Psychology Review, 25*(1), 45–65. https://doi.org/10.1016/j.cpr.2004.07.008

Anttila, V., & Luoma, J. (2005). Surrogate in-vehicle information systems and driver behaviour in an urban environment: A field study on the effects of visual and cognitive load. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2), 121–133. https://doi.org/10.1016/j.trf.2005.04.007

Baldo, N., Marini, A., & Miani, M. (2020). Drivers' braking behavior affected by cognitive distractions: An experimental investigation with a virtual car simulator. *Behavioral Sciences, 10*(10), 150. https://doi.org/10.3390/bs10100150

Bella, F., Natale, V., & Silvestri, M. (2017). Driver-pedestrian interaction under different road environments. *Transportation Research Procedia, 27*, 148–155. https://doi.org/10.1016/j.trpro.2017.12.093

Bella, F., & Silvestri, M. (2015). Effects of safety measures on driver's speed behavior at pedestrian crossings. *Accident Analysis & Prevention, 83*, 111–124. https://doi.org/10.1016/j.aap.2015.07.016

Bertulis, T., & Dulaski, D. M. (2014). Driver approach speed and its impact on driver yielding to pedestrian behavior at unsignalized crosswalks. *Transportation Research Record: Journal of the Transportation Research Board, 2464*, 46–51. https://doi.org/10.3141/2464-06

Bhagavathula, R., & Gibbons, R. B. (2023). Lighting Strategies to Increase Nighttime Pedestrian Visibility at Midblock Crosswalks. *Sustainability, 15*(2), 1455. https://doi.org/10.3390/su15021455

Black, A. A., Brough, D., King, M., King, N., Bentley, L. A., Fylan, F., & Wood, J. M. (2023). Making night-time pedestrians safer using innovative clothing designs. *Transportation Research Part F: Traffic Psychology and Behaviour, 94*, 321–328. https://doi.org/10.1016/j.trf.2023.03.002

Bobermin, M. P., Silva, M. M., & Ferreira, S. (2021). Driving simulators to evaluate road geometric design effects on driver behaviour: A systematic review. *Accident Analysis & Prevention, 150*, Article 105923. https://doi.org/10.1016/j.aap.2020.105923

Borowsky, A., Oron-Gilad, T., & Parmet, Y. (2009). Age and skill differences in classifying hazardous traffic scenes. *Transportation Research Part F: Traffic Psychology and Behaviour, 12*(4), 277–287. https://doi.org/10.1016/j.trf.2009.02.001

Borowsky, A., Shinar, D., & Oron-Gilad, T. (2010). Age, skill, and hazard perception in driving. *Accident Analysis & Prevention, 42*(4), 1240–1249. https://doi.org/10.1016/j.aap.2010.02.001

Calvi, A., D'Amico, F., Ferrante, C., & Bianchini Ciampoli, L. (2020). Effectiveness of augmented reality warnings on driving behaviour whilst approaching pedestrian crossings: A driving simulator study. *Accident Analysis & Prevention, 147*, Article 105760. https://doi.org/10.1016/j.aap.2020.105760

Charlton, J. L., Oxley, J., Fildes, B., Oxley, P., Newstead, S., Koppel, S., & O'Hare, M. (2006). Characteristics of older drivers who adopt self-regulatory driving behaviours. *Transportation Research Part F: Traffic Psychology and Behaviour, 9*(5), 363–373. https://doi.org/10.1016/j.trf.2006.06.006

Chipman, M., & Jin, Y. L. (2009). Drowsy drivers: The effect of light and circadian rhythm on crash occurrence. *Safety Science, 47*(10), 1364–1370. https://doi.org/10.1016/j.ssci.2009.03.005

Choudhary, P., & Velaga, N. R. (2017). Modelling driver distraction effects due to mobile phone use on reaction time. *Transportation Research Part C: Emerging Technologies, 77*, 351–365. https://doi.org/10.1016/j.trc.2017.02.007

Cloutier, M. S., Lachapelle, U., d'Amours-Ouellet, A. A., Bergeron, J., Lord, S., & Torres, J. (2017). "Outta my way!" Individual and environmental correlates of interactions between pedestrians and vehicles during street crossings. *Accident Analysis & Prevention, 104*, 36–45. https://doi.org/10.1016/j.aap.2017.04.015

D'Addario, P., & Donmez, B. (2019). The effect of cognitive distraction on perception-response time to unexpected abrupt and gradually onset roadway hazards. *Accident Analysis & Prevention, 127*, 177–185. https://doi.org/10.1016/j.aap.2019.03.003

Dallaway, N., E. Lucas, S. J., & Ring, C. (2022). Cognitive tasks elicit mental fatigue and impair subsequent physical task endurance: Effects of task duration and type. *Psychophysiology*, *59*(12), e14126. Doi: 10.1111/psyp.14126.

Dawson, J. D., Uc, E. Y., Anderson, S. W., Johnson, A. M., & Rizzo, M. (2010). Neuropsychological predictors of driving errors in older adults. *Journal of the American Geriatrics Society, 58*(6), 1090. https://doi.org/10.1111/j.1532-5415.2010.02872.x

Department for Transport (2024). Reported road casualties Great Britain, annual report: 2023. https://www.gov.uk/government/statistics/reported-road-casualties-great-britain-annual-report-2023/reported-road-casualties-great-britain-annual-report-2023#:~:text=In%20reported%20road%20collisions%20in,little%20change%20compared%20to%202022.

Department for Transport (2025). Road safety statistics: data tables. https://www.gov.uk/government/statistical-data-sets/reported-road-accidents-vehicles-and-casualties-tables-for-great-britain#factors-contributing-to-collisions-and-casualties-ras07.

Depestele, S., Ross, V., Verstraelen, S., Brijs, K., Brijs, T., Van Dun, K., & Meesen, R. (2020). The impact of cognitive functioning on driving performance of older persons in comparison to younger age groups: A systematic review. *Transportation Research Part F: Traffic Psychology and Behaviour, 73*, 433–452. https://doi.org/10.1016/j.trf.2020.07.009

Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 8*(2), 97–120. https://doi.org/10.1016/j.trf.2005.04.012

Evans, T., Stuckey, R., & Macdonald, W. (2022). Young drivers' perception of hazards: Variation with experience and day versus night. *Transportation Research Part F: Traffic Psychology and Behaviour, 88*, 258–280. https://doi.org/10.1016/j.trf.2022.05.017

Folli, M., & Bennett, J. M. (2023). Factors that predict hazard perception in older adult road-users: A systematic review. *Transportation Research Part F: Traffic Psychology and Behaviour, 99*, 19–35. https://doi.org/10.1016/j.trf.2023.10.008

Fotios, S., Robbins, C. J., Fox, S. R., Cheal, C., & Rowe, R. (2021). The effect of distraction, response mode and age on peripheral target detection to inform studies of lighting for driving. *Lighting Research & Technology, 53*(7), 637–656.

Fylan, F., King, M., Brough, D., Black, A. A., King, N., Bentley, L. A., & Wood, J. M. (2020). Increasing conspicuity on night-time roads: Perspectives from cyclists and runners. *Transportation Research Part F: Traffic Psychology and Behaviour, 68*, 161–170. https://doi.org/10.1016/j.trf.2019.11.016

Gallucci, M. (2019). *GAMLj: General analyses for linear models*. [jamovi module]. Retrieved from https://gamlj.github.io/.

Garay-Vega, L., Fisher, D. L., & Pollatsek, A. (2007). Hazard anticipation of novice and experienced drivers. *Transportation Research Record, 2009*, 1–7. https://doi.org/10.3141/2009-01

Goodridge, C. M., Gonçalves, R. C., Arabian, A., Horrobin, A., Solernou, A., Lee, Y. T., Lee, Y. M., Madigan, R., & Merat, N. (2024). Gaze entropy metrics for mental workload estimation are heterogenous during hands-off level 2 automation. *Accident Analysis & Prevention, 202*, Article 107560. https://doi.org/10.1016/j.aap.2024.107560

Gorrini, A., Crociani, L., Vizzari, G., & Bandini, S. (2018). Observation results on pedestrian-vehicle interactions at non-signalized intersections towards simulation. *Transportation Research Part F: Traffic Psychology and Behaviour, 59*, 269–285. https://doi.org/10.1016/j.trf.2018.09.016

Haque, M. M., & Washington, S. (2014). A parametric duration model of the reaction times of drivers distracted by mobile phone conversations. *Accident Analysis & Prevention, 62*, 42–53. https://doi.org/10.1016/j.aap.2013.09.010

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident Analysis & Prevention, 39*(2), 372–379. https://doi.org/10.1016/j.aap.2006.08.013

Harrison, X. A. (2014). Using observation-level random effects to model overdispersion in count data in ecology and evolution. *PeerJ, 2*, e616.

Hebert Martinez, K. L., & Porter, B. E. (2004). The likelihood of becoming a pedestrian fatality and drivers' knowledge of pedestrian rights and responsibilities in the Commonwealth of Virginia. *Transportation Research Part F: Traffic Psychology and Behaviour, 7*(1), 43–58. https://doi.org/10.1016/j.trf.2003.11.001

Hossain, A., Sun, X., Thapa, R., Hossain, M. M., & Das, S. (2023). Exploring association of contributing factors to pedestrian fatal and severe injury crashes under dark-no-streetlight condition. *IATSS Research, 47*(2), 214–224. https://doi.org/10.1016/j.iatssr.2023.03.002

Hossain, M. M., Zhou, H., Sun, X., Hossain, A., & Das, S. (2024). Crashes involving distracted pedestrians: Identifying risk factors and their relationships to pedestrian severity levels and distraction modes. *Accident Analysis & Prevention, 194*, Article 107359. https://doi.org/10.1016/j.aap.2023.107359

International Organization for Standardization (2016). ISO 17488:2016, Road vehicles—Transport information and control systems—Detection-response task (DRT) for assessing attentional effects of cognitive load in driving. https://www.iso.org/standard/59887.html.

Jazayeri, A., Martinez, J. R. B., Loeb, H. S., & Yang, C. C. (2021). The Impact of driver distraction and secondary tasks with and without other co-occurring driving behaviors on the level of road traffic crashes. *Accident Analysis & Prevention, 153*, Article 106010. https://doi.org/10.1016/j.aap.2021.106010

Kalantari, A. H., Yang, Y., de Pedro, J. G., Lee, Y. M., Horrobin, A., Solernou, A., Holmes, C., Merat, N., & Markkula, G. (2023). Who goes first? a distributed simulator study of vehicle–pedestrian interaction. *Accident Analysis & Prevention, 186*, Article 107050. https://doi.org/10.1016/j.aap.2023.107050

Karthaus, M., Wascher, E., Falkenstein, M., & Getzmann, S. (2020). The ability of young, middle-aged and older drivers to inhibit visual and auditory distraction in a driving simulator task. *Transportation Research Part F: Traffic Psychology and Behaviour, 68*, 272–284. https://doi.org/10.1016/j.trf.2019.11.007

Kemnitzer, C. R., Pope, C. N., Nwosu, A., Zhao, S., Wei, L., & Zhu, M. (2019). An investigation of driver, pedestrian, and environmental characteristics and resulting pedestrian injury. *Traffic Injury Prevention, 20*(5), 510–514. https://doi.org/10.1080/15389588.2019.1612886

Khan, N. A., & Habib, M. A. (2022). Exploring the impacts of built environment on pedestrian injury severity involving distracted driving. *Journal of Safety Research, 80*, 97–108. https://doi.org/10.1016/j.jsr.2021.11.001

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). *The impact of driver inattention on near-crash/crash risk: An analysis using the 100-car naturalistic driving study data (No. DOT. HS (810)*. In United States: Department of Transportation. National Highway Traffic Safety Administration.

Kountouriotis, G., & Merat, N. (2016). Leading to distraction: Driver distraction, lead car, and road environment. *Accident Analysis & Prevention, 89*, 22–30. https://doi.org/10.1016/j.aap.2015.12.027

Krizsik, N., & Sipos, T. (2024). The effect of driver and pedestrian distraction factors on giving priority at designated pedestrian crossings. *Transportation Research Part F: Traffic Psychology and Behaviour, 104*, 109–117. https://doi.org/10.1016/j.trf.2024.05.013

Kutela, B., Oscar, C., Kidando, E., & Mihayo, M. (2023). Seeing through eyes of Drivers: Space consideration in investigating visibility of Vulnerable road users involved in crashes from Driver's perspective. *Accident Analysis & Prevention, 192*, Article 107260. https://doi.org/10.1016/j.aap.2023.107260

Kwan, I., & Mapstone, J. (2004). Visibility aids for pedestrians and cyclists: A systematic review of randomised controlled trials. *Accident Analysis & Prevention, 36*(3), 305–312. https://doi.org/10.1016/S0001-4575(03)00008-3

Leden, L., Gårder, P., & Johansson, C. (2006). Safe pedestrian crossings for children and elderly. *Accident Analysis & Prevention, 38*(2), 289–294. https://doi.org/10.1016/j.aap.2005.09.012

Lee, C., & Abdel-Aty, M. (2005). Comprehensive analysis of vehicle–pedestrian crashes at intersections in Florida. *Accident Analysis & Prevention, 37*(4), 775–786. https://doi.org/10.1016/j.aap.2005.03.019

Lee, S. E., Klauer, S. G., B. Olsen, E. C., Simons-Morton, B. G., Dingus, T. A., Ramsey, D. J., & Ouimet, M. C. (2008). Detection of Road Hazards by Novice Teen and Experienced Adult Drivers. *Transportation Research Record: Journal of the Transportation Research Board. 2078*, 26-32. Doi: 10.3141/2078-04.

Li, T., Klavins, J., Xu, T., Zafri, N. M., & Stern, R. (2025). Identifying built environment factors influencing driver yielding behavior at unsignalized intersections: A naturalistic open-source dataset collected in Minnesota. *Journal of Safety Research, 92*, 331–345. https://doi.org/10.1016/j.jsr.2024.12.006

Lubbe, N., & Davidsson, J. (2015). Drivers' comfort boundaries in pedestrian crossings: A study in driver braking characteristics as a function of pedestrian walking speed. *Safety Science, 75*, 100–106. https://doi.org/10.1016/j.ssci.2015.01.019

Madigan, R., Lee, Y. M., & Merat, N. (2021). Validating a methodology for understanding pedestrian–vehicle interactions: A comparison of video and field observations. *Transportation Research Part F: Traffic Psychology and Behaviour, 81*, 101–114. https://doi.org/10.1016/j.trf.2021.05.006

Madigan, R., Lee, Y. M., Lyu, W., Horn, S., Garcia de Pedro, J., & Merat, N. (2023). Pedestrian interactions with automated vehicles: Does the presence of a zebra crossing affect how eHMIs and movement patterns are interpreted? *Transportation Research Part F: Traffic Psychology and Behaviour, 98*, 170–185. https://doi.org/10.1016/j.trf.2023.09.003

Markkula, G., Madigan, R., Nathanael, D., Portouli, E., Lee, Y. M., Dietrich, A., & Merat, N. (2020). Defining interactions: A conceptual framework for understanding interactive behaviour in human and automated road traffic. *Theoretical Issues in Ergonomics Science, 21*(6), 728–752.

McGwin, G., Chapman, V., & Owsley, C. (2000). Visual risk factors for driving difficulty among older drivers. *Accident Analysis & Prevention, 32*(6), 735–744. https://doi.org/10.1016/S0001-4575(99)00123-2

McKnight, A., & McKnight, A. (2003). Young novice drivers: Careless or clueless? *Accident Analysis & Prevention, 35*(6), 921–925. https://doi.org/10.1016/S0001-4575(02)00100-8

Mehler, B., Reimer, B., & Dusek, J. A. (2011). *MIT AgeLab delayed digit recall task (n-back)*. Cambridge, MA: Massachusetts Institute of Technology.

Mitman, M. F., Ragland, D. R., & Zegeer, C. V. (2008). Marked-Crosswalk Dilemma. *Transportation Research Record: Journal of the Transportation Research Board, 2073*, 86–93. https://doi.org/10.3141/2073-10

Obeid, H., Abkarian, H., Abou-Zeid, M., & Kaysi, I. (2017). Analyzing driver-pedestrian interaction in a mixed-street environment using a driving simulator. *Accident Analysis & Prevention, 108*, 56–65. https://doi.org/10.1016/j.aap.2017.08.005

O'Toole, S. E., Christie, N., & Poulter, D. (2025). Driver compliance with the 2022 UK highway code rule on giving way to pedestrians at side roads: A naturalistic observation study. *Journal of Urban Mobility, 8*, 100140. https://doi.org/10.1016/j.urbmob.2025.100140

Oviedo-Trespalacios, O., & Regan, M. A. (2021). Driver Distraction. *International Encyclopedia of Transportation*, 113–120. https://doi.org/10.1016/B978-0-08-102671-7.10669-4

Owens, D. A., Wood, J. M., & Owens, J. M. (2007). Effects of age and illumination on night driving: A road test. *Human Factors, 49*(6), 1115–1131. https://doi.org/10.1518/001872007X249974

Öztürk, İ., Horrobin, A., Garcia de Pedro, J., Rowe, R., Fotios, S., & Merat, N. (2024). *LED strips for pedestrian conspicuity: A driving simulator study investigating the experiences of younger and older drivers during daylight and after dark conditions.* [Oral presentation]. International Cooperation on Theories and Concepts in Traffic safety. the Hague, the Netherlands.

Öztürk, İ., Merat, N., Rowe, R., & Fotios, S. (2023). The effect of cognitive load on Detection-Response Task (DRT) performance during day- and night-time driving: A driving simulator study with young and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 97*, 155–169. https://doi.org/10.1016/j.trf.2023.07.002

Papadakaki, M., Kontogiannis, T., Tzamalouka, G., Darviri, C., & Chliaoutakis, J. (2008). Exploring the effects of lifestyle, sleep factors and driving behaviors on sleep-related road risk: A study of Greek drivers. *Accident Analysis & Prevention, 40*(6), 2029–2036. https://doi.org/10.1016/j.aap.2008.08.019

Papantoniou, P., Papadimitriou, E., & Yannis, G. (2017). Review of driving performance parameters critical for distracted driving research. *Transportation Research Procedia, 25*, 1796–1805. https://doi.org/10.1016/j.trpro.2017.05.148

Pour-Rouholamin, M., & Zhou, H. (2016). Investigating the risk factors associated with pedestrian injury severity in Illinois. *Journal of Safety Research, 57*, 9–17. https://doi.org/10.1016/j.jsr.2016.03.004

Pradhan, A. K., Pollatsek, A., Knodler, M., & Fisher, D. L. (2009). Can younger drivers be trained to scan for information that will reduce their risk in roadway traffic scenarios that are hard to identify as hazardous? *Ergonomics, 52*(6), 657–673. https://doi.org/10.1080/00140130802550232

R Core Team (2022). *R: A Language and environment for statistical computing*. (Version 4.1) [Computer software]. Retrieved from https://cran.r-project.org. (R packages retrieved from CRAN snapshot 2023-04-07).

Ranchet, M., Brémond, R., Pala, P., Colomb, M., & Cavallo, V. (2022). The detection of vulnerable road users by younger and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 91*, 357–367. https://doi.org/10.1016/j.trf.2022.10.018

Regan, M. A., Hallett, C., & Gordon, C. P. (2011). Driver distraction and driver inattention: Definition, relationship and taxonomy. *Accident Analysis & Prevention, 43*(5), 1771–1781. https://doi.org/10.1016/j.aap.2011.04.008

Regan, M. A., & Oviedo-Trespalacios, O. (2022). Driver distraction: mechanisms, evidence, prevention, and mitigation. In *The vision zero handbook: Theory, technology and management for a zero casualty policy* (pp. 995–1056). Cham: Springer International Publishing.

Robbins, C., & Fotios, S. (2022). The prevalence of in-vehicle driving distractions in road traffic collisions as a function of road type. *Transportation Research Part F: Traffic Psychology and Behaviour, 84*, 211–222. https://doi.org/10.1016/j.trf.2021.11.019

Rogé, J., & Pébayle, T. (2009). Deterioration of the useful visual field with ageing during simulated driving in traffic and its possible consequences for road safety. *Safety Science, 47*(9), 1271–1276. https://doi.org/10.1016/j.ssci.2009.03.012

Rogé, J., Ndiaye, D., & Vienne, F. (2014). Useful visual field training: A way to improve elderly car drivers' ability to detect vulnerable road users. *Transportation Research Part F: Traffic Psychology and Behaviour, 26*, 246–257. https://doi.org/10.1016/j.trf.2014.08.005

Rolison, J. J., & Moutari, S. (2020). Combinations of factors contribute to young driver crashes. *Journal of Safety Research, 73*, 171–177. https://doi.org/10.1016/j.jsr.2020.02.017

Rosenbloom, T., Nemrodov, D., & Eliyahu, A. B. (2006). Yielding behavior of israeli drivers: interaction of age and sex. *Perceptual and Motor Skills, 103*, 387–390. https://doi.org/10.2466/pms.103.2.387-390

Salon, D., & McIntyre, A. (2018). Determinants of pedestrian and bicyclist crash severity by party at fault in San Francisco, CA. *Accident Analysis & Prevention, 110*, 149–160. https://doi.org/10.1016/j.aap.2017.11.007

Santolino, M., Céspedes, L., & Ayuso, M. (2022). The impact of aging drivers and vehicles on the injury severity of crash victims. *International Journal of Environmental Research and Public Health, 19*(24), 17097. https://doi.org/10.3390/ijerph192417097

Savage, S. W., Spano, L. P., & Bowers, A. R. (2019). The effects of age and cognitive load on peripheral-detection performance. *Journal of Vision, 19*(1), 1–17. https://doi.org/10.1167/19.1.15

Schneider, R. J., & Sanders, R. L. (2019). Pedestrian safety practitioners' perspectives of driver yielding behavior across North America. *Transportation Research Record: Journal of the Transportation Research Board, 2519*, 39–50. https://doi.org/10.3141/2519-05

Schneider, R. J., Qin, X., Shaon, M. R. R., Sanatizadeh, A., He, Z., Wkyhuis, P., & Bill, A. (2017). *Evaluation of driver yielding to pedestrians at uncontrolled crosswalks*. Madison, WI, USA: University of Wisconsin-Madison Traffic Operations and Safety (TOPS) Laboratory.

Schneider, R. J., Sanatizadeh, A., Rahman Shaon, M. R., He, Z., & Qin, X. (2018). Exploratory analysis of driver yielding at low-speed, uncontrolled crosswalks in Milwaukee, Wisconsin. *Transportation Research Record: Journal of the Transportation Research Board, 2672*(35), 21–32. https://doi.org/10.1177/0361198118782251

Singh, H., & Kathuria, A. (2021). Analyzing driver behavior under naturalistic driving conditions: A review. *Accident Analysis & Prevention, 150*, Article 105908. https://doi.org/10.1016/j.aap.2020.105908

Soares, S., Ferreira, S., & Couto, A. (2020). Driving simulator experiments to study drowsiness: A systematic review. *Traffic Injury Prevention, 21*(1), 29–37. https://doi.org/10.1080/15389588.2019.1706088

Steinhauser, K., Leist, F., Maier, K., Michel, V., Pärsch, N., Rigley, P., Wurm, F., & Steinhauser, M. (2018). Effects of emotions on driving behavior. *Transportation Research Part F: Traffic Psychology and Behaviour, 59*, 150–163. https://doi.org/10.1016/j.trf.2018.08.012

Sucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis & Prevention, 102*, 41–50. https://doi.org/10.1016/j.aap.2017.02.018

Sundfør, H. B., Sagberg, F., & Høye, A. (2019). Inattention and distraction in fatal road crashes – results from in-depth crash investigations in Norway. *Accident Analysis & Prevention, 125*, 152–157. https://doi.org/10.1016/j.aap.2019.02.004

The Highway Code (2023). The Highway Code. https://www.highwaycodeuk.co.uk.

The jamovi project (2023). *jamovi*. (Version 2.4) [Computer Software]. Retrieved from https://www.jamovi.org.

Tyrrell, R. A., Wood, J. M., Owens, D. A., Whetsel Borzendowski, S., & Stafford Sewall, A. (2016). The conspicuity of pedestrians at night: A review. *Clinical and Experimental Optometry, 99*(5), 425–434.

UK Government (n.d.). Using a phone, sat nav or other device when driving. Retrieved from: https://www.gov.uk/using-mobile-phones-when-driving-the-law#:~:text=Using%20devices%20hands%2Dfree,at%20any%20time%20during%20usage.

Uttley, J., & Fotios, S. (2017). The effect of ambient light condition on road traffic collisions involving pedestrians on pedestrian crossings. *Accident Analysis & Prevention, 108*, 189–200. https://doi.org/10.1016/j.aap.2017.09.005

Üzümcüoğlu, Y., Öztürk, İ., & Özkan, T. (2020). Differences in traffic climate between driving simulation scenarios with different complexity levels. *Nesne Psikoloji Dergisi, 8*(17), 171–179. https://doi.org/10.7816/nesne-08-17-01

Vidal-Tortosa, E., & Lovelace, R. (2024). Road lighting and cycling: A review of the academic literature and policy guidelines. *Journal of Cycling and Micromobility Research, 2*, Article 100008. https://doi.org/10.1016/j.jcmr.2023.100008

Wagner, J. T., & Nef, T. (2011). Cognition and driving in older persons. *Swiss Medical Weekly, 141*(0102), w13136–w. https://doi.org/10.4414/smw.2011.13136

Widodo, A. F., Chen, C., Chan, C. W., Saleh, W., Wiratama, B. S., & Pai, C. W. (2023). Walking against traffic and pedestrian injuries in the United Kingdom: New insights. *BMC Public Health, 23*(1), 2205.

Wood, J. M. (2020). Nighttime driving: Visual, lighting and visibility challenges. *Ophthalmic and Physiological Optics, 40*(2), 187–201. https://doi.org/10.1111/opo.12659

Wood, J. M. (2023). Improving the conspicuity and safety of pedestrians and cyclists on night-time roads. *Clinical and experimental optometry, 106*(3), 227–237. https://doi.org/10.1080/08164622.2023.2174001

Wood, J. M., Black, A. A., & Tyrrell, R. A. (2022). Increasing the conspicuity of cyclists at night by using bicycle lights and clothing to highlight their biological motion to oncoming drivers. *Transportation Research part F: Traffic Psychology and Behaviour, 90*, 326–332. https://doi.org/10.1016/j.trf.2022.09.005

Wood, J. M., Lacherez, P., & Tyrrell, R. A. (2014). Seeing pedestrians at night: Effect of driver age and visual abilities. *Ophthalmic and Physiological Optics, 34*(4), 452–458. https://doi.org/10.1111/opo.12139

Wood, J. M., Tyrrell, R. A., & Carberry, T. P. (2005). Limitations in drivers' ability to recognize pedestrians at night. *Human factors, 47*(3), 644–653. https://doi.org/10.1518/001872005774859980

World Health Organisation (2023). Global status report on road safety 2023. https://www.who.int/publications/i/item/9789240086517.

Wood, JM., Tyrrell, R. A., Lacherez, P., & Black, A. A. (2017). Night-time pedestrian conspicuity: Effects of clothing on drivers' eye movements. *Ophthalmic and Physiological Optics, 37*(2), 184–190. https://doi.org/10.1111/opo.12351

Yared, T., & Patterson, P. (2020). The impact of navigation system display size and environmental illumination on young driver mental workload. *Transportation Research Part F: Traffic Psychology and Behaviour, 74*, 330–344. https://doi.org/10.1016/j.trf.2020.08.027

Yue, L., Abdel-Aty, M., Wu, Y., Zheng, O., & Yuan, J. (2020). In-depth approach for identifying crash causation patterns and its implications for pedestrian crash prevention. *Journal of Safety Research, 73*, 119–132. https://doi.org/10.1016/j.jsr.2020.02.020

Zhang, G., Liang, Q., Jiang, X., Yang, S., Fan, Y., Qiu, X., & Mao, C. (2022). Examining the causal effects of distracted driving on crash injury severities. *Journal of Transportation Safety & Security, 14*(8), 1358–1377. https://doi.org/10.1080/19439962.2021.1923102