Accident Analysis and Prevention 197 (2024) 107418

Contents lists available at ScienceDirect

Accident Analysis and Prevention

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

The effect of rear bicycle light configurations on drivers' perception of cyclists' presence and proximity

Daniel T. Bishop [a,b,*], Huma Waheed [b], Tamara S. Dkaidek [a,b], David P. Broadbent [a,b,c]

[a] Centre for Cognitive Neuroscience, College of Health, Medicine and Life Sciences, Brunel University London, United Kingdom
[b] Division of Sport, Health and Exercise Sciences, Department of Life Sciences, Brunel University London, United Kingdom
[c] Centre for Sport Research, Institute for Physical Activity and Nutrition, Deakin University, Burwood, Australia

ARTICLE INFO

Keywords:
Collision
Cycle
Safety
Smart technology
Vulnerable road user

ABSTRACT

The optimal cycle light configuration for maximizing cyclists' conspicuity to drivers is not clear. Advances in sensor technology has led to the development of 'reactive' cycle lights that detect changes in the environment and consequently increase their flashing speed and brightness in risky situations – for example, when a rearward car is approaching – but no research has examined the effect of such lights on driver perception. The aim of the present study is to compare different cycle light configurations, including 'reactive' light technology, on drivers' ability to detect cyclists and estimate their proximity. We recruited 32 drivers to participate in two experiments, in which they viewed life-size real-world stimuli filmed from a driver's perspective in daytime and at dusk. The footage showed a cyclist on a bicycle with a rear light mounted on the seat post, in various configurations: *static light*, *steady flashing*, *reactive flashing* and *no light*. In Experiment 1, the drivers were required to detect the presence or absence of a cyclist on the road ahead as quickly as possible. In Experiment 2, they were required to estimate the distance of the cyclist from their vehicle, and to rate their confidence in their estimates. Experiment 1 revealed that drivers were quicker to detect the cyclist's presence in all rear cycle light conditions relative to the no light condition, but there were no differences in speed or accuracy across rear light conditions. Experiment 2 showed that drivers were more accurate in estimating the cyclist's proximity in the steady flashing and reactive flashing conditions, compared to static and no light conditions. Drivers were also more confident in their judgements in all rear light conditions compared to the no light condition. In conclusion, flashing rear cycle lights, regardless of reactive technology, enhanced drivers' perception of a cyclist ahead, notably in terms of their judgements of distance to that cyclist. Further investigation is needed to fully understand the impact of cycle light technology on driver perception, as well as the use of drivers' distance-to-cyclist estimates as an index of cyclists' cognitive conspicuity.

1. Introduction

Personal safety concerns, notably regarding collisions with motor vehicles, are a fundamental barrier to cycling (Pearson et al., 2023). These safety concerns appear well founded as hospital admissions, police statistics and national databases show that cyclists are frequent casualties in road traffic incidents (Björnstig et al., 2017). In fact, cyclists are overrepresented in road injury statistics in many countries including the UK (Department for Transport, 2023), Australia (O'Hern & Oxley, 2018) and France (Bouaoun et al., 2015). Research into collisions and near-misses involving cyclists frequently implicate road users' misallocation of attention or distraction (Møller et al., 2021; Salmon et al., 2022; Useche et al., 2018). In fact, a common contributory factor to bicycle and vehicle collisions is that the driver 'looked but failed to see' the cyclist prior to the collision (Herslund & Jørgensen, 2003; Prati et al., 2018). Given that drivers' ability to detect a cyclist is partly determined by the cyclist's visibility (Rogé et al., 2017), it is vital to develop methods for increasing drivers' ability to rapidly detect and identify cyclists.

In the UK, it is a legal requirement for bicycle lights to be used at night to ensure cyclists are visible to drivers. However, in the daytime, where most cyclist casualties occur (Transport for London, 2014), cyclists are more visible, and so the use of bicycle lights are encouraged to not only enhance the visibility of cyclists, but also increase their

---

* Corresponding author at: Brunel University London, HNZW 203, Heinz Wolff Building, Kingston Lane, Uxbridge, Middlesex UB8 3PH, United Kingdom.
E-mail addresses: daniel.bishop@brunel.ac.uk (D.T. Bishop), tamara.dkaidek@brunel.ac.uk (T.S. Dkaidek).

https://doi.org/10.1016/j.aap.2023.107418
Received 11 July 2023; Received in revised form 13 November 2023; Accepted 30 November 2023

conspicuity (Fotios and Castleton, 2017; Thornley et al., 2008). Visual conspicuity has been defined as the tendency of an object to stand out from its background (Langham & Moberly, 2003), and is driven by bottom-up attentional processes. For example, a driver's attention is automatically captured by a traffic light changing colour from green to red. Cognitive conspicuity relates to top-down attentional processes, whereby the observer's attentional focus is determined by their current goals, expectations and/or prior knowledge of the environment (Rogé et al., 2017). For example, cyclists may be more conspicuous to a motorist driving on a familiar route that is known to have cyclist-supportive infrastructure.

Bicycle-mounted safety lights appear to be effective at decreasing on-road collisions by increasing the cyclist's visual conspicuity (Kwan & Mapstone, 2004). For example, Madsen and colleagues (2013) fitted permanent running lights to the bicycles of 1,845 cyclists and compared the incident rate in this group to a control group of 2,000 cyclists, over a one-year period. The rate for the former was 19 % lower than that of the latter. In a related study, Lahrmann et al. (2018) conducted two randomised controlled trials, in which they examined the effects of permanent running lights and high-visibility jackets on cyclists' safety. In the first study, they fitted permanent running lights to 1,845 participants' bicycles and a further 2,000 participants formed a comparison control group with no lights attached to their bicycles. All participants reported every accident they were involved in, once every two months over a one-year period, regardless of the accident severity. A total of 255 accidents were reported (7 per 100 cyclists), but the incidence rate was 47 % lower for the group with permanent running lights. This may be due to drivers adapting their behaviour in the presence of more conspicuous cyclists (Black et al., 2020). However, several factors can affect the visual conspicuity of a road user, including weather and light conditions, visual clutter, and the size of the object to be detected (Fotios and Castleton, 2017; Rogé et al., 2019). With this in mind, cycling safety researchers have started to examine ways in which visual conspicuity can be manipulated using various bicycle light configurations to make cyclists stand out more to drivers.

Many commercially available cycle lights have various features, such as static and steady flashing light modes, but research into the relative effectiveness of these different configurations is limited. Recent exceptions are studies conducted by Edewaard et al. (2017), Edewaard et al. (2020), who found that drivers rated cyclists as more conspicuous during daylight hours when steady flashing rear cycle lights were mounted on the seat post, compared to an 'always on' static light configuration. This is consistent with evidence to show that abrupt onsets and offsets lead to exogenous capture of attention (Kawahara et al., 2012). Building on these findings, Edewaard et al. (2019) examined the effects of five different rear bicycle light configurations – no light, static seat post light, steady flashing seat post light, static heel lights, and a warping triangle (static seat post & heel lights combined) – on the ability of drivers to detect and recognise a cyclist. The participants' gaze behaviour was recorded as they viewed driver point-of-view vi. deos of a roadway during daylight hours for each bicycle light configuration. The participants' initial fixations on the cyclist occurred at distances 2.7 times greater than those at which they subsequently identified them, but there were no differences in fixation times across the different light configurations. However, the cyclist was identified significantly earlier in steady flashing or static seat post light conditions, relative to no light and warping triangle conditions. The authors argued that the flashing and static seat post light may have accelerated processing time, and therefore recognition, by being more representative of cyclists than other vulnerable road users, thereby enhancing their cognitive conspicuity as well as their visual conspicuity.

Recent technological developments in cycle lights have seen the integration of sensor technology to create *reactive* flashing bicycle lights (e.g., https://seesense.cc/). These reactive bicycle lights can detect potentially hazardous situations, such as rearward approaching vehicles, and respond to these events with an increased flashing rate and/or light intensity, to increase the cyclist's conspicuity (MacArthur et al., 2019). There is evidence to show that flickering stimuli such as flashing lights are more effective when the flicker pattern deviates from the observer's expectations (Stolte & Ansorge, 2021); such novelty is a key determinant of attentional 'popout' (Strayer & Johnston, 2000). There is also evidence that faster brake light flashing rates in leading vehicles can quicken the following driver's response times (Hsieh et al., 2022). However, to or knowledge, there is currently no research comparing this new reactive flashing cycle light technology to typical static and steady flashing modes, to determine which configuration may optimize drivers' ability to perceive cyclists in the road ahead quickly and accurately.

1.1. *Study aims*

Based on the evidence presented above, cycle-mounted lighting can make cyclists more conspicuous to motorists and therefore more perceptible. However, the effects of different lighting configurations – notably, reactive rear cycle light technology – have received little research attention. The aim of the present study was to test the effectiveness of four different rear cycle light configurations (*no light*, *static*, *steady flashing*, *reactive flashing*) on (a) drivers' ability to detect the presence of a cyclist on the road ahead, and (b) to estimate the distance from their vehicle to a cyclist, and their confidence in doing so. Earlier cyclist detection and more proximal judgements of cyclist distance will increase the time available for drivers to react to cyclists, potentially reducing the frequency and severity of collisions.

We recruited a sample of experienced drivers to take part in two laboratory-based experiments in which they sat in a simulated driving setup and viewed life-size real-world vi. deo simulations at daytime and at dusk. In Experiment 1, we recorded the speed and accuracy with which the drivers detected the presence/absence of a cyclist. In Experiment 2, the drivers' task was to estimate the distance between their vehicle and a cyclist ahead in the road, and to rate their confidence in their decisions. We predicted that all light configurations would yield superior cyclist detection, distance estimates, and confidence relative to a no light condition, and that flashing lights would be superior to static ones. We also expected that a reactive flashing pattern would be superior to a steady flashing pattern due to its greater novelty, and therefore greater cognitive conspicuity. Additionally, given the potential effect of age on driver perception (Borowsky et al., 2010; Moran et al., 2019), we conducted secondary analyses to examine the correlation between participant age and their responses in each of the cycle light conditions in both experiments. There is also evidence to suggest gender differences in driver confidence (e.g., Wayne & Miller, 2018), so we conducted an additional secondary analysis in Experiment 2 to compare male and female participants' confidence in their distance estimates.

2. Material and methods

2.1. *Participants and study design*

Thirty-two participants (14 females, 18 males) aged 18–78 years ($M = 31.09$ yrs, $SD = 16.64$ yrs, $Median = 22$ yrs) took part in the study. A power analysis was performed for sample size estimation using G*Power 3.1. For repeated measures ANOVA (within factors) with one group and four conditions, a required sample size of 24 was estimated, given a medium effect size of 0.25, an alpha of 0.05 and a power of 0.8. We recruited an additional six participants to mitigate potential attrition.

All participants had held a driver's license for at least 6 months ($M = 11.28$ yrs, $SD = 15.4$ yrs), and drove 0–35 h per week at the time of the study ($M = 8.41$ hrs, $SD = 8.81$ hrs; six participants reported 0 h of driving per week). Because there is evidence that cyclists make better drivers (Beanland & Hansen, 2017), we asked participants to report their cycling experience. Twelve of the participants reported that they cycled. These participants had been cycling for 1–70 years ($M = 18.36$ yrs, $SD = 24.73$ yrs) and currently cycled 0–45 h per month ($M = 10.67$ hrs, $SD =$

15.28 hrs). All participants reported that their vision and hearing were normal or corrected-to-normal.

Participants completed two repeated measures experiments to examine how different rear cycle light settings affected their perception of a cyclist, in terms of their presence/absence and their distance of the cyclist from the vehicle. Due to technical issues, data for one participant was not collected for Experiment 2. The study was approved by the research ethics committee of the lead institution.

2.2. *Test stimuli*

The vi. deo footage used in both experiments was captured using a 170-degree field-of-view camera (GoPro Hero 5; GoPro Inc. CA) mounted off-center of the dashboard in a small-five-seater vehicle with a right-hand driving position, common to the UK, to closely replicate the perspective of a driver positioned rearward to a cyclist. The filming took place on a single stretch of a major road in the UK approximately one mile in length that comprised both single- and dual-carriageway sections, as well as multiple roundabouts. Filming was completed on the same day in daytime and at dusk. The speed limit on this road was 40 mph and there were other road users, predominantly motorists, on the road throughout the filming (see Supplementary Materials for example clips). For Experiment 1, vi. deo footage was collected in which no cyclist was visible. For Experiment 2, a cyclist (the first author) was always on the road ahead of the filming vehicle.

2.2.1. *Experiment 1 – Cyclist detection*

Vi. deo acquisition. Twenty-four different clips were created from the test stimuli, none of which contained any cyclists on the road. A cyclist (the third author) was filmed separately, in a greenscreen studio, as they cycled on a stationary bicycle, the rear wheel of which was mounted on a cycle trainer. The bicycle was fitted with a See.Sense ACE rear cycle light (https://seesense.cc/; dimensions 60 mm × 33 mm, 23 mm; 125 lm) on the bicycle seat post. This product offers three light configurations: *static*, *steady flashing*, and *reactive flashing*; the light was switched off in a *no light* condition. In the three light configuration conditions, the 125 lm LED board was lit to varying extents: In the *static* condition, the whole LED board remained on constantly, but in the *steady flashing* condition the top and bottom sections of the board flashed alternately. In the *reactive flashing* condition, the alternating pattern remains, but the light automatically flashes brighter and faster in reaction to environmental conditions such as the headlights of rearward approaching vehicles; this is achieved via proprietary sensor technology. In the greenscreen studio, the reactive pattern was triggered by the researcher rapidly motioning a bright light source (Exposure Joystick; 1,150 lm) towards the cycle light. One greenscreen clip was created for each of the four experimental conditions.

Vi. deo editing. The greenscreen vi. deo clips created were superimposed over the cyclist-free footage in Adobe Premiere Pro (Adobe, San Jose, CA), in a separate editing track; green sections of the clip were replaced by cloning sections of the roadway footage. The cyclist vi. deo clips were resized such that the cyclist's proportions were consistent with the backdrop footage. Keyframes were used to facilitate resizing at multiple junctures in each clip, to account for variation in the filming vehicle's speed of approach, and therefore the apparent distance of the cyclist from the driver. Additionally, vi. deo paths were created for the cyclist in Adobe Premiere Pro, such that they appeared to follow the changing trajectory of the road, to increase the authenticity of the vi. deo clips. The footage excerpts were identical across experimental conditions, and the cyclist position was somewhat distal. Fig. 1 shows a screenshot taken from an Experiment 1 vi. deo clip in the no light condition (representative full vi. deo clips are provided in Supplementary Materials).

2.2.2. *Experiment 2 – Distance and confidence estimates*

Vi. deo acquisition. During the collection of the vi. deo footage, the filming vehicle would approach a cyclist (the first author) on the road ahead. The cyclist, who was wearing a cycle helmet (Lazer O2; Lazer, Milton Keynes, UK), black cycle shorts, a dark gray long-sleeved top, a high-visibility gilet, and a backpack (Osprey Solo; Osprey, Poole, UK), maintained a steady cycling speed of approximately 15 mph while the filming vehicle approached and then overtook them in a safe manner. Some sections of the road included designated cycling routes, not segregated from motor traffic, which the cyclist used. For the other sections of the road, the cyclist adopted a riding position that conformed to the UK National Standard for Cycle Training (DfT & DVSA, 2019) and the UK Highway Code.

Throughout vi. deo acquisition, the See.Sense ACE rear cycle light was attached to the bicycle seat post. The same four light settings as Experiment 1 were recorded for the Experiment 2 footage – *no light*, *static*, *steady flashing*, and *reactive flashing*. The light settings were frequently and systematically changed throughout the vi. deo acquisition to ensure that meteorological and ambient conditions were comparable across the experimental conditions. The reactive flashing

Fig. 1. Experiment 1 – Screenshot (Cyclist in Cycle Lane; No Light Condition; Light Rain).

pattern was mostly triggered by rearward approaching vehicle headlights and/or abrupt changes to the road surface (e.g., intact-to-disrupted).

Video editing. The video footage was edited in Adobe Premiere Pro (Adobe, San Jose, CA) to create a series of 129 clips comprising at least 5 s of viable footage. Each trial was coded in Excel (Microsoft, WA, United States), to note the experimental condition (*none*, *static*, *steady flashing*, *reactive flashing*), the time of day (daytime, dusk), weather conditions (e.g., overcast, light rain) and the single- and dual-carriageway direction (northbound, southbound), to create equivalence across conditions. Twenty-four appropriate clips were selected and edited to create the four rear light conditions – a total of 96 clips. Each trial lasted approximately five seconds, including a two-second freeze-frame at its beginning. Each video clip was edited such that it occluded as the filming vehicle neared the cyclist, at varying distances. Editing was performed to create equivalence across experimental conditions not only in terms of these distances, but also the weather (e.g., sunny, light rain) and visibility (e.g., overcast, twilight) conditions under which filming took place. Fig. 2 shows a screenshot taken immediately prior to the occlusion point for one clip in the static light condition (video clips also provided in Supplementary Materials).

The distance between the filming vehicle and the cyclist was approximated for each trial. To do so, we used six reference trials from the experiment that had identifiable environmental features (e.g., bus stops, road markings, roadside drains) that aligned with either the lower-left corner of the filming vehicle windscreen or the bottom of the rear bicycle wheel at the moment the footage was occluded, in each clip. The real-world distances between these environmental features had previously been measured by the first author, using a measuring wheel (Trumeter 5000, Trumeter, Bury, UK). With these values, and those obtained from measuring the on-screen distances with a ruler as viewed on a 22-inch monitor (Dell, TX, United States), we were able to identify the ratio of real-world meters to an on-screen millimeter. This value was used as a multiplier for all subsequent on-screen measurements, to determine approximate real-world distances for each video clip used in every experimental condition.

To ascertain whether there were significant differences in the approximated distance between the filming vehicle and the cyclist across light conditions, a one-way repeated measures ANOVA was conducted. Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 7.509$, $p = .186$. There was an effect of condition, $F(3,69) = 3.256$, $p = .027$, $\eta_p^2 = 0.124$. Bonferroni pairwise comparisons revealed that the filming vehicle was significantly closer to the cyclist in the *steady flashing* condition ($M = 5.719$ m, $SD = 2.165$ m) than in the *no light* condition ($M = 7.085$ m, $SD = 2.421$ m), $p = .020$. The distances between the filming vehicle and the cyclist in the *static* condition ($M = 6.779$ m, $SD = 2.159$) and the *reactive flashing* condition ($M = 6.340$ m, $SD = 2.705$) were not significantly different from one another, or from the other rear cycle light conditions, p's > 0.05. These findings are taken into consideration in our interpretation of the findings from Experiment 2.

2.3. Procedure

In both experiments, participants sat in front of a 4.1 × 2.3 m projection screen (AV Stumpfl, Wallern, Austria) onto which the video clips were projected via an NEC PE401H projector (NEC, Tokyo, Japan). They sat in a chair that afforded the driver's perspective, or more precisely, that of the dashboard-mounted camera in the filming vehicle. The participants adopted the role of a driver, in a simulated setup (Fig. 3) that comprised a table-mounted steering wheel and foot pedals (Logitech Driving Force GT, Lausanne, Switzerland), although participants' use of the steering wheel, driving console or pedals did not elicit corresponding changes in the video footage. The trials were presented to the participant via experiment generator software (E-Prime v. 2.0, Psychology Software Tools, Inc., Pittsburgh, PA).

2.3.1. Experiment 1 – Cyclist detection

In this experiment, there were five test blocks comprising 18 trials each – a total of 90 trials. Three video clips from each of the four rear cycle light conditions (*no light*, *static*, *steady flashing*, *reactive flashing*) were equally distributed across blocks. There were 30 trials from which the cyclist was absent; these were also equally distributed across the five test blocks – i.e., six cyclist-absent trials in each block, a ratio of 1 in every three trials. The order of trials was randomized within blocks.

The participant responded by clicking the right paddle shifter on the steering wheel setup when they thought the cyclist was present and clicking the left paddle shifter when they thought the cyclist was absent. As soon as the participant responded, the trial ended, a 2-second gray screen appeared, and then the next trial began. Response accuracy and response time were automatically collected via E-Prime. The video clips repeated on a loop if participants took longer than three seconds to

Fig. 2. Experiment 2 – Screenshot Prior to Occlusion (Cyclist on road; Static Light Condition; Near Dusk).

Fig. 3. Experimental Setup (Image from Experiment 2).

respond. However, our pilot testing showed that response times were typically shorter than this, as reflected in the final dataset (see *Results*).

2.3.2. *Experiment 2 – Distance and confidence estimates*

In this experiment, participants completed four test blocks, with 24 trials in each test block – a total of 96 trials. There were 24 trials for each of the four rear light experimental conditions (*no light*, *static*, *steady flashing*, *reactive flashing*) that were equally distributed across the four test blocks – i.e., six trials for each condition in each block. The order of trials was randomized within blocks. After each trial was occluded, the participant was required to estimate the distance between the car and the bicycle, in meters, as well as rating their confidence in their estimate, on a 10-point Likert scale ranging from 0 (not at all confident) to 10 (extremely confident) that appeared on screen; they provided both responses verbally. The researcher noted down the participant's responses for each trial before the participant was asked to advance to the next trial by pressing a button on the steering wheel. At quasi-random intervals every 3–6 trials, participants were asked to respond to the question "Did the car nearest to you have its brake lights on?", by replying 'yes', 'no' or 'not sure'. This question was used to encourage the participant to maintain normal visual search behavior when driving, rather than exclusively focusing on the cyclist. If the participant answered correctly the researcher responded, "Yes, well done". If they answered incorrectly, the researcher responded, "That was incorrect. Please pay attention to the other road users as you would when driving". If the participant was unsure, the researcher responded, "Okay. Please pay attention to the other road users as you would when driving". Participants correctly answered the question 85.67 % of the time (SD = 14.30; Range = 25–100 %), suggesting an appropriate level of engagement with this secondary task. These data were not used in any the main analyses.

2.4. *Measures*

2.4.1. *Experiment 1 – Cyclist detection*

2.4.1.1. *Response accuracy.*

Participants were required to correctly identify if there was a cyclist on the road or not in each trial by clicking the right (cyclist present) or left (no cyclist present) paddle shifter on the steering wheel. Response accuracy was expressed as the percentage of correct responses in each experimental condition.

2.4.1.2. *Response time.*

Response time was calculated as the difference between the onset of the vi. deo and the participant's response. This was reported in milliseconds.

2.4.2. *Experiment 2 – Distance and confidence estimates*

2.4.2.1. *Distance estimate.*

Participants were required to report their estimate of the distance between the front of the car and the rear wheel of the bicycle, in meters. The main purpose of this measure was to compare the estimates across experimental conditions, rather than to determine participants' accuracy.

2.4.2.2. *Difference between estimated and actual distances.*

To account for significant differences in the approximate distance between the car and the cyclist in the rear cycle light conditions (reported in section 2.2.1), a difference score was calculated by subtracting participants' estimated distances from the actual approximated distances in each trial.

2.4.2.3. *Confidence rating.*

After providing each distance estimation, participants were required to rate their confidence in their estimation on a scale from 0 'Very unconfident' to 10 'Very confident'.

2.5. *Data analysis*

All data were screened for outliers and non-normality prior to analysis.

In Experiment 1, there were 48 trials (1.7 % of trials) for which participants' responses were longer than three seconds. However, none of these were statistical outliers and were retained. Response accuracy and response time were compared across experimental conditions using separate one-way repeated measures ANOVAs. Response accuracy and response time were also compared between all trials in which the cyclist was present and trials in which they were absent, using a paired-sample *t*-test. Secondary correlational analyses were conducted to explore the relationship between the participant's age and response accuracy and response time in each rear cycle light condition and in the No Cyclist condition.

For Experiment 2, to compare distance estimation and confidence ratings across rear cycle light conditions, separate one-way repeated measures ANOVAs were used. To assess the accuracy of the estimated distance in each condition, the difference between the participants' estimated distance and the actual approximated distance was compared across conditions using a one-way repeated measures ANOVA. As with the first experiment, secondary correlational analyses were conducted to explore the relationship between the participant's age and distance estimation and confidence ratings in each experimental condition. An additional secondary analysis was conducted using independent sample t-tests, or the non-parametric alternative, to compare confidence ratings between the male and female participants.

In the case of violations of Mauchly's test of sphericity, the Greenhouse-Geisser correction was applied. Alpha was set at 0.05 and for effect sizes, partial eta squared (η_p^2) was used for ANOVAs and Cohens *d* was used for t-tests. In the case of significant main effects for ANOVA, Bonferroni pairwise comparisons were used for follow-up analysis.

3. Results

3.1. Experiment 1 – Cyclist detection

3.1.1. Response accuracy

When comparing the accuracy of identifying the presence/absence of a cyclist across the four conditions, Mauchly's Test of Sphericity indicated that the assumption of sphericity had not been violated, $\chi^2(2) = 0.503$, $p = .992$. A one-way repeated measures ANOVA revealed no significant differences in response accuracy between conditions, $F(3,93) = 0.611$, $p = .609$, $\eta_p^2 = 0.019$. Response accuracy in all conditions was above 90 %, suggesting a ceiling effect (see Table 1).

A paired samples *t*-test revealed no significant difference in response accuracy on trials where there was a cyclist ($M = 92.969$ %, $SD = 14.657$ %) in the road ahead and when there was no cyclist ($M = 92.292$ %, $SD = 16.141$ %), t(31) = 0.549, $p = .587$, $d = 0.026$, 95 % CI = 1.835 – 3.188.

3.1.2. Response time

When comparing response times for identifying the cyclist in the rear cycle light conditions, Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $\chi^2(2) = 51.113$, $p < .001$, and therefore, a Greenhouse-Geisser correction was applied, ε = 0.496. A one-way repeated measures ANOVA revealed no significant differences in response time between conditions, $F(3,93) = 0.1.221$, $p = .307$, $\eta_p^2 = 0.038$ (see Table 1).

A paired samples *t*-test revealed a significant difference in response time on trials where there was a cyclist ($M = 802.632$ ms, $SD = 288.161$ ms) in the road ahead and when there was no cyclist ($M = 1085.610$ ms, $SD = 562.003$ ms), $t(31) = 0.4.712$, $p < .001$, $d = 0.634$, 95 % CI = 398.295 – 157.662.

Table 1
Mean (SD) Response Accuracy and Response Time – All Conditions.

	Response Accuracy		Response Time	
	Mean (%)	Standard Deviation	Mean (ms)	Standard Deviation
No light	93.124	15.839	829.129	324.221
Static	92.708	15.367	775.563	295.626
Steady Flashing	93.750	13.853	819.700	294.908
Reactive Flashing	92.292	15.530	806.135	309.214
No Cyclist	92.292	16.141	1085.610	562.003

3.1.3. Secondary analyses

To explore the relationship between the participant's age and response accuracy and response time in each experimental condition, a Spearman Rank Order correlation was conducted as the data was not normally distributed and was heterogeneous. Spearman Rank correlations revealed significant positive relationships between the participant's age and response times across all experimental conditions (No Light, $r = 0.530$, $p = .002$; Static, $r = 0.462$, $p = .008$; Flashing, $r = 0.570$, $p < .001$; Reactive, $r = 0.539$, $p = .001$; and No Cyclist, $r = 0.582$, $p < .001$). In contrast, there was no significant relationship between the participant's age and response accuracy in any of the experimental conditions (No Light, $r = 0.164$, $p = .370$; Static, $r = 0.015$, $p = .935$; Flashing, $r = 0.068$, $p = .712$; Reactive, $r = 0.099$, $p = .590$; and No Cyclist, $r = -0.039$, $p = .830$). These analyses suggest age-related decline in response times but not in response accuracy.

3.2. Experiment 2 – Distance and confidence estimates

3.2.1. Distance estimates

Mauchly's Test of Sphericity indicated that sphericity had been violated, $\chi^2(2) = 17.008$, $p = .005$, and therefore, a Greenhouse-Geisser correction was applied, ε = 0.720. A one-way repeated measures ANOVA revealed a significant effect of rear cycle light condition on estimated distances, $F(2.160,64.794) = 21.437$, $p < .001$, $\eta_p^2 = 0.417$. Bonferroni pairwise comparisons revealed that participants estimated the distance between the car and cyclist to be shorter in the *steady flashing* condition than their estimates for all other conditions, p's < 0.001 (Fig. 4). There were no other significant differences between conditions. These findings align somewhat with the significant differences found between conditions for the approximated actual distances between the filming vehicle and the cyclist (reported in Section 2.2.1).

3.2.2. Difference scores – Estimated and approximated actual distances

Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $\chi^2(2) = 16.585$, $p = .005$, and therefore, a Greenhouse-Geisser correction was applied, ε = 0.727. A one-way repeated measures ANOVA revealed a significant difference between conditions for the difference scores, $F(2.181,65.424) = 47.601$, $p < .001$, $\eta_p^2 = 0.613$. Bonferroni pairwise comparisons revealed that the difference between the participants' estimated distance and the approximated actual distance was significantly greater (i.e., lower accuracy) in the *no light* condition than in all other conditions, p's < 0.05 (see Fig. 5). The difference between the participants' estimated distance and the approximated actual distance was also significantly greater in the *static* condition relative to the *steady flashing* and *reactive flashing* conditions, p's < 0.05, suggesting greater accuracy in the latter conditions. There was no difference between the *steady flashing* condition and *reactive flashing* condition, $p = .062$.

3.2.3. Confidence ratings

Mauchly's Test of Sphericity indicated that sphericity had not been violated, $\chi^2(2) = 6.583$, $p = .254$. There was a significant effect of condition on participants' confidence in their distance estimation, $F(3,90) = 6.755$, $p < .001$, $\eta_p^2 = 0.184$. Bonferroni pairwise comparisons revealed

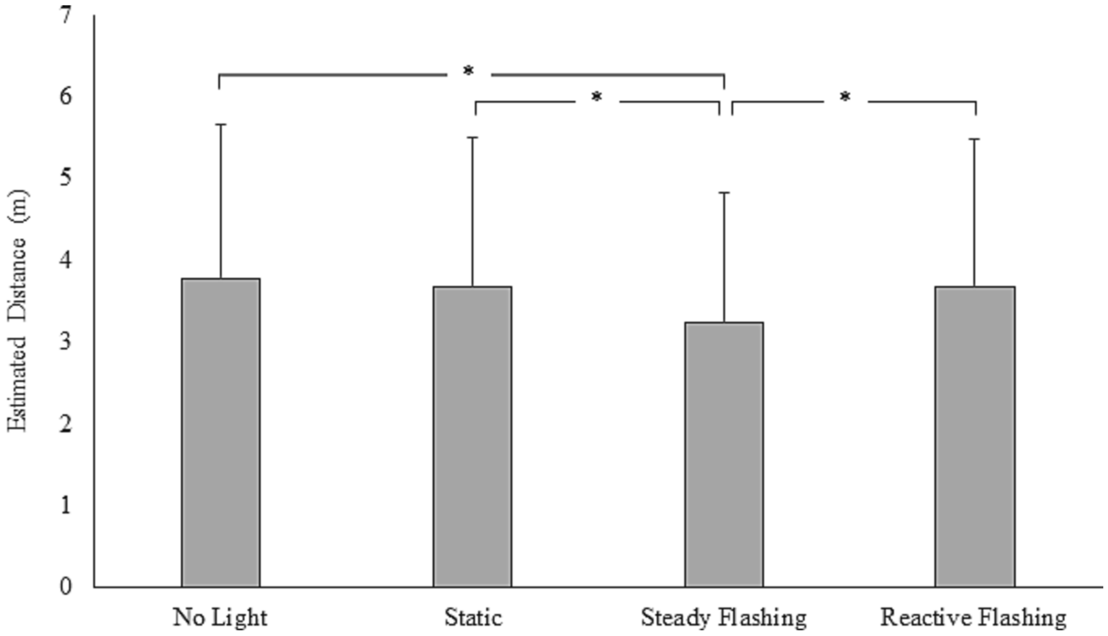

Fig. 4. Mean (±1 SD) Estimated Distance (m) Between the Filming Vehicle and the Cyclist, by Condition. Note. *p <.001.

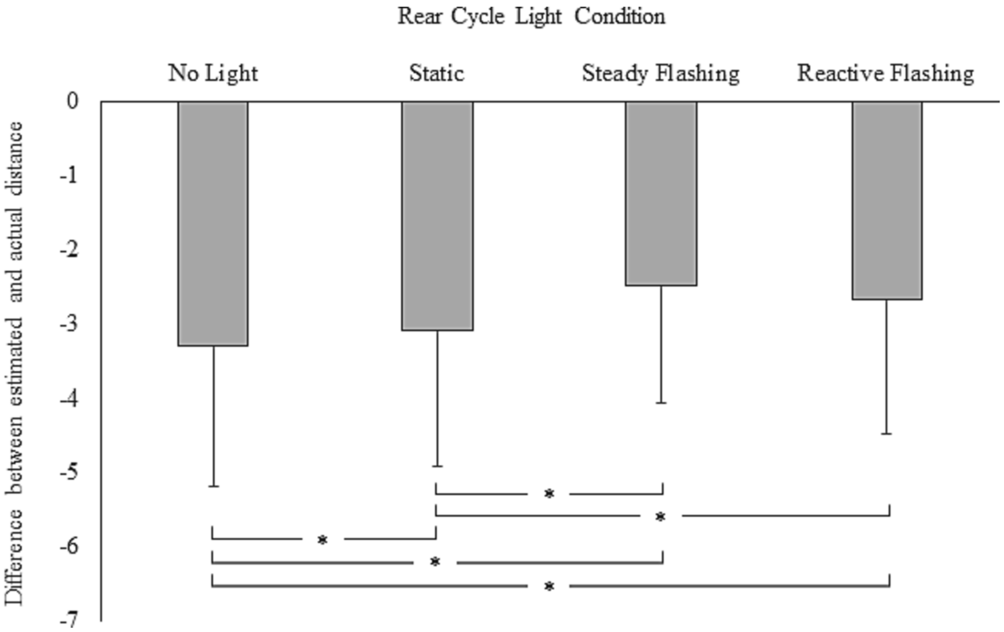

Fig. 5. Mean (±1SD) Difference between Participants' Estimated Distance and the Approximated Actual Distance between the Filming Vehicle and the Cyclist, by Condition. Note. Differences closer to zero are better estimates, irrespective of over- or under-estimation. *p <.05.

that the participants were significantly less confident in their distance estimation in the *no light* condition compared to all other conditions, *p's* < 0.05 (Fig. 6). There were no other significant differences between the conditions.

3.2.4. Secondary analyses

To explore the relationship between participant age and distance estimation and confidence ratings in each experimental condition, Spearman Rank Order correlations were conducted as the data were non-normal and heterogeneous. There were no significant relationships between participant age and distance estimation in any of the rear cycle light conditions (No Light, r_s = -0.227, p =.218; Static, r_s = -0.192, p =.302; Flashing, r_s = -0.224, p =.226; Reactive, r_s = -0.205, p =.270). Similarly, there were no significant relationships between participant age and confidence ratings (No Light, r_s = 0.279, p =.129; Static, r_s = 0.163, p =.380; Flashing, r_s = 0.006, p =.975; Reactive, r_s = 0.144, p =.439).

Due to the nonparametric nature of the data, Mann-Whitney tests were conducted to compare male and female participants' confidence ratings. The tests revealed that male participants were significantly more confident than female participants in the Static (M_{male} = 7.373, SD_{male} = 1.008, M_{female} = 6.688, SD_{female} = 0.794; U = 68.500, z = -2.006, p =.045, d = 0.755), Flashing (M_{male} = 7.433, SD_{male} = 0.906, M_{female} = 6.732, SD_{female} = 0.895; U = 62.000, z = -2.264, p =.024, d = 0.778), and Reactive (M_{male} = 7.412, SD_{male} = 1.004, M_{female} = 6.729, SD_{female} = 0.831; U = 69.500, z = -1.966, p =.049, d = 0.741) rear cycle light

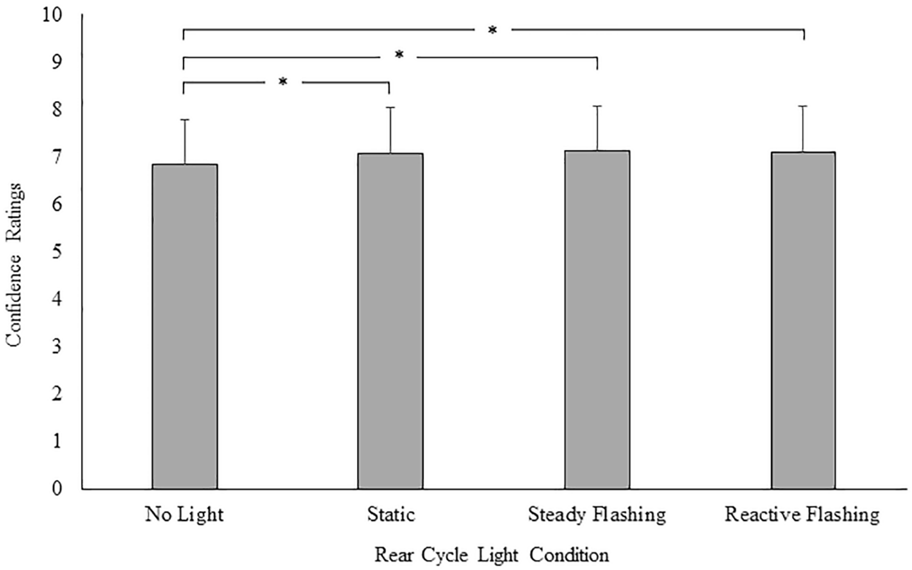

Fig. 6. Mean (±1 SD) Confidence Ratings for Estimating Distance (m) Between the Filming Vehicle and the Cyclist, by Condition. Note. *p <.001.

conditions. There was no gender difference in confidence in the No Light condition ($M_{male} = 7.060$, $SD_{male} = 1.017$, $M_{female} = 6.557$, $SD_{female} = 0.859$; $U = 83.500$, $z = -1.410$, $p = .159$, $d = 0.535$).

Taken together, these secondary analyses suggest no age-related effects on distance estimations or confidence rating, although males appear to be more confident in their distance estimations overall.

4. Discussion

Cyclists are overrepresented in road injury statistics, and a leading cause of this is collisions with motor vehicles. In many of these collisions, drivers looked but failed to see the cyclist, a phenomenon that can be mitigated by increasing cyclists' conspicuity. With this in mind, the paucity of research examining the effect of different cycle light configurations on drivers' ability to detect a cyclist and estimate their proximity is surprising. Many commercially available rear cycle lights offer multiple modes of operation, notably static and steady flashing light patterns. The latest technological developments in bicycle lights include sensor-driven 'reactive' flashing light sequences that flash quicker and brighter according to changes in the immediate environment, such as a rearward approaching motor vehicle. However, there has been no research examining the effect of this technology on cyclists' conspicuity. In two related experiments, we tested the efficacy of several rear cycle light configurations, including 'reactive' flashing, for improving drivers' perception of cyclists in dynamic simulated road scenes filmed in daytime and at dusk.

In Experiment 1, contrary to our predictions, while drivers were quicker to detect the presence of a cyclist relative to their absence, there were no differences between the cycle light conditions in terms of the drivers' accuracy or response times. This contradicts previous research which suggests that cycle lights increase the cyclist's visual conspicuity in daytime hours (Edewaard et al., 2019; Edewaard et al., 2020; Fotios and Castleton, 2017). However, Edewaard et al. (2019) found no difference in the ability of various rear cycle light configurations to quicken participants' initial fixations on a cyclist. The authors suggested that this may be because their participants were able to detect the shape of the entire cyclist from a distance in daylight in the absence of rear cycle lights. This may be the case for the current findings too but given the evidence for the effectiveness of cycle lights for decreasing collisions during daytime hours (Lahrmann et al., 2018; Madsen et al., 2013), it may still be prudent for cyclists to use rear cycle lights during daylight hours, to increase their conspicuity to motorists. This may be especially important given that by 2030 it is estimated that older adults will account for 1 in every 4 drivers in the Organization for Economic Cooperation and Development (OECD) member countries (OECD, 2001). Relatedly, secondary analyses in Experiment 1 revealed an age-related decline in response times across all experimental conditions, so optimization of light configurations to facilitate older drivers' recognition and response times to cyclists ahead in the road could be critical. Further research is required to examine the impact of cycle light configurations on younger and older drivers' visual search behaviour in daytime – specifically early fixation on a cyclist – as well as the use of the visual information obtained to identify and respond to the cyclist quickly and safely.

In Experiment 2, all cycle light conditions resulted in more accurate estimations of the cyclists' proximity to the motor vehicle compared to when the cycle light was off, and there was no effect of age on distance estimation. However, it is noteworthy that drivers' confidence in their estimations was lower in the no light condition compared to all other conditions, and this was driven by higher confidence ratings by male participants. Such judgement confidence, or *decision-making self-efficacy*, as it has been termed, has been shown to improve the efficiency of decision making in dynamic sport contexts (Hepler & Feltz, 2012; Hepler, 2016), so could arguably also do so when driving. This is more important when considering the cognitive demands faced by drivers and effects of these demands on their gaze behavior and driving performance (Broadbent et al., 2023). These findings add to existing evidence for the effectiveness of rear cycle lights in enhancing cyclists' visual and cognitive conspicuity and therefore drivers' estimations of the proximity of cyclists in the road ahead (cf. Edewaard et al., 2017; Edewaard et al., 2019; Edewaard et al., 2020).

Experiment 2 also provided evidence for the benefits of using a flashing rear cycle light, whether it be consistent flashes or variable flashes, compared to a static light mode (cf. Edewaard et al., 2017; Edewaard et al., 2019; Edewaard et al., 2020). Steady and reactive flashing patterns both resulted in more accurate estimations of the cyclists' proximity to the motor vehicle than did a static light configuration. As visual conspicuity is driven by bottom-up attentional processes (Langham & Moberly, 2003), we speculate that flashing light configurations cause the cyclist to 'pop out' more from their immediate environment (Kawahara et al., 2012) and therefore capture drivers' attention more effectively than static lights. Furthermore, it has been argued that a flashing light in one centralized location (e.g., on the seat post) may increase the cyclist's cognitive conspicuity, because drivers have learned that such light configurations are prototypical for cyclists (Edewaard et al., 2020). Hence, there may be an additive effect, in terms of visual and cognitive conspicuity, of a centrally located flashing light. Tin Tin et al. (2015) investigated the relationship between cyclist conspicuity and bike-motor vehicle crashes, in a sample of 2,590 New Zealand cyclists. The cyclists' visual conspicuity was determined by the extent of their use of high-visibility garments, materials, and cycle lights, and their cognitive conspicuity was classified according to the prevalence of cyclists in the region. In the low bike-use city of Auckland, crash risk was higher and interestingly, visually conspicuous cyclists were at greater risk than in other locations. The interactive effects of visual and cognitive conspicuity are clearly nuanced and require further investigation.

Contrary to our predictions, there was no apparent advantage of a reactive flashing pattern, over and above a steady flashing pattern, in either experiment. As there is evidence that variable flicker patterns are attention-grabbing (Stolte & Ansorge, 2021), we had expected that the novelty and 'popout' of the reactive flashing pattern would increase the visual conspicuity relative to a steady flashing light and consequently enhance the detection of the cyclist as well as the estimation of the cyclists' proximity to the vehicle. It is possible that changes in intensity of the reactive flashings were less conspicuous in daylight, or that changes in flash rate were so subtle as to be subliminal, although there is evidence that subliminal stimuli can elicit attentional capture (Schoeberl et al., 2015). Further research is required that systematically manipulates relative light intensities and flashing frequencies to address these speculations.

4.1. Strengths and limitations

A strength of this study is that we used real-world vi. deo stimuli in both experiments, rather than computer-generated images used previously (e.g., Rogé et al., 2017). This arguably increases the realism for the driver participants, and therefore their 'embodiment' in the decision-making process, while still providing a degree of experimental control that cannot be achieved in real-world settings (e.g., Black et al., 2020; Edewaard et al., 2020). That said, the design of the study would have been enhanced by using a more immersive driving simulator setup to increase the drivers' embodiment, or the inclusion of a real-world counterpart experiment with which we could compare the laboratory findings. We did not capture data relating to participants' perceptions of the realism and immersivity of the experimental setup; such ratings have been successfully used to demonstrate the effectiveness of road-based immersive training (e.g., Bishop et al., 2023). Furthermore, while we only included participants with self-reported normal or corrected-to-normal vision, it would have been an improvement to include objective measures of vision, perception, and cognitive abilities to account for individual differences in hazard perception when driving (Barragán & Lee, 2021, Broadbent et al., 2023; Mackenzie & Harris, 2017; Wood et al., 2016).

The design of the study could have been further enhanced by testing the various light configurations under different meteorological conditions (i.e., rain, sunshine, overcast) and road complexities (e.g., rural, inner city) in a more systematic manner. While slightly different weather conditions were observed when recording the footage, and the road complexity changed across trials (e.g., single- to multi-lane road), these weren't sufficiently different to define and so it was beyond the scope of this current study to examine them systematically. Future research should look to systematically examine the effect of different bicycle light configurations on driver perception at different times of the day, weather conditions, and road complexities to obtain fuller insight into the factors influencing cyclists' visibility and conspicuity.

Another strength of the study is that we examined not only drivers' ability to detect cyclists, but also their ability to accurately estimate the distance of the cyclist from their vehicle, as well as their confidence in their judgements, which we propose as a potential index of cyclists' cognitive conspicuity to drivers. In Experiment 1, the cyclist's cognitive conspicuity was high, as the participants could expect to see a cyclist present in the vi. deo footage frequently – in 2 out of 3 trials, on average – so the findings of this experiment arguably reflected the cyclist's visual conspicuity only. However, in Experiment 2, participants knew that a cyclist would always be present – they also had three seconds to detect the cyclist in each trial – and so visual and cognitive conspicuity in all conditions were both high. Therefore, any differences in cognitive conspicuity might have resulted from differences in the relevance of the cyclist to the drivers' objectives, one of which is to avoid collisions with other road users. We tentatively suggest that because flashing lights imply a sense of urgency (e.g., in the case of emergency vehicles) the looming cyclist may be perceived as more imminent, increasing the perceived likelihood of an impending collision (Hancock, 2019), thereby leading to more rapid driver responses (cf. Hsieh et al., 2022).

The absence of any significant differences between detection accuracy or response times across experimental conditions in Experiment 1 might be due to the slight artificiality of the stimuli. Despite our endeavors to ensure the realism of the vi. deo clips, the superimposed cyclist might have 'popped out' from the background footage, due either to trajectories that might have appeared somewhat unnatural compared to those of a cyclist actually moving along the roadway in the real world, or to differences between ambient light conditions in the greenscreen studio and the road environment; such differences cannot easily be rectified in the postediting process. However, the former could be improved by using camera tracks for filming, which would eliminate changes in the lateral positioning of the filming camera and thereby facilitate accurate superimposition during postedit – although this would also require exclusive access to a suitable roadway. The latter could be mitigated by recording greenscreen clips under the same natural light conditions as those in the counterpart real-world footage. Additionally, Experiment 2, would have been improved with more precise measurements of the actual distance between the cyclist and the filming vehicle; for example, via the use of sensor technology to measure distances in real-time.

4.2. Conclusion

In two related experiments, we demonstrated that, in daytime and at dusk, a rear-mounted cycle light enabled quicker and more confident recognition of cyclists by drivers compared to when the rear cycle light was turned off, and that flashing rear cycle light modes, be they steady or reactive, may result in more accurate estimations of the cyclist's proximity to the driver's vehicle when compared to a static light mode. We found no additional benefits of a reactive rear cycle light mode relative to a steady flashing mode, although further research is required to examine the effect of reactive technology on cyclists' visual and cognitive conspicuity. In conclusion, we recommend that cyclists should always use rear cycle lights, and that cyclists should use flashing light modes to maximize their visibility and conspicuity to rearward drivers.

CRediT authorship contribution statement

Daniel T. Bishop: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Huma Waheed:** Data curation, Investigation, Project administration, Resources. **Tamara S. Dkaidek:** Data curation, Investigation, Project administration, Resources. **David P. Broadbent:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The company See.Sense were the external partner required as a precondition for allocation of funds from the Brunel Innovation Voucher scheme; the intention is to use such projects as a catalyst for future collaborative funding bids. The See.Sense Directors wanted to determine the efficacy of their product – notably the reactive flashing mode – for improving cyclist conspicuity. They also provided the Ace rear cycle light that we used during acquisition of the vi. deo footage used in the study. We have acknowledged their contributions in their Acknowledgements section of the paper and in the graphical abstract (the company logo).We feel this potential competing interest is mitigated by our findings, which support the use of steady flashing lights, not reactive lights, to improve drivers' perception of cyclists. Steady flashing modes are a common feature of many rear cycle lights, produced by multiple manufacturers globally. Hence, no advantage will be conferred to See. Sense in the marketplace.

Data availability

Data will be made available on request.

Acknowledgements

We wish to extend our gratitude to the 32 participants who gave their time to take part in this study, without whom we would not have been able to yield the insights manifested in this paper.

We are also grateful to our colleagues Hitesh Patel and Bal Ghoman for proactively helping to make this research project happen.

Finally, thank you to colleagues at See.Sense, who were willing for us to conduct an objective empirical test of one of their products, the Ace rear cycle light. Thank you also for providing the light for filming.

Funding Source

This work was supported by a grant from the Brunel Innovation Voucher Scheme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aap.2023.107418.

References

Barragán, D., Lee, Y.C., 2021. Individual differences predict drivers hazard perception skills. International Journal of Human Factors and Ergonomics 8 (2), 195–213. https://doi.org/10.1504/IJHFE.2021.116073.

Beanland, V., Hansen, L.J., 2017. Do cyclists make better drivers? Associations between cycling experience and change detection in road scenes. Accident Analysis and Prevention 106, 420–427. https://doi.org/10.1016/j.aap.2017.07.013.

Bishop, D. T., Daylamani-Zad, D., Dkaidek, T. S., Fukaya, K., & Broadbent, D. P. (2023). A Brief Gamified Immersive Intervention to Improve 11-14-year-olds' Cycling-Related Looking Behaviour and Situation Awareness: A Pilot Study.

Björnstig, J., Bylund, P., Björnstig, U., 2017. Vehicle-related injuries in and around a medium sized Swedish City - bicyclist injuries caused the heaviest burden on the medical sector. Injury Epidemiology 4 (1), 4. https://doi.org/10.1186/s40621-016-0101-8.

Black, A.A., Duff, R., Hutchinson, M., Ng, I., Phillips, K., Rose, K., Ussher, A., Wood, J.M., 2020. Effects of night-time bicycling visibility aids on vehicle passing distance. Accident Analysis & Prevention 144, N.PAG. https://doi.org/10.1016/j.aap.2020.105636.

Borowsky, A., Shinar, D., Oron-Gilad, T., 2010. Age, skill, and hazard perception in driving. Accident Analysis & Prevention 42 (4), 1240–1249.

Bouaoun, L., Haddak, M.M., Amoros, E., 2015. Road crash fatality rates in France: A comparison of road user types, taking account of travel practices. Accident Analysis and Prevention 75, 217–225. https://doi.org/10.1016/j.aap.2014.10.025.

Broadbent, D.P., D'Innocenzo, G., Ellmers, T.J., Parsler, J., Szameitat, A.J., Bishop, D.T., 2023. Cognitive load, working memory capacity and driving performance: A preliminary fNIRS and eye tracking study. Transportation Research: Part F 92, 121–132. https://doi.org/10.1016/j.trf.2022.11.013.

Department for Transport. (2023). *Reported road casualties Great Britain, provisional results: 2022.*. London, UK: Department for Transport. https://www.gov.uk/government/statistics/reported-road-casualties-great-britain-provisional-results-2022/reported-road-casualties-great-britain-provisional-results-2022.

Edewaard, D. E., Fekety, D. K., Szubski, E. C., & Tyrrell, R. A. (2020). Highlighting bicyclist biological motion enhances their conspicuity in daylight. *Accident Analysis and Prevention, 142*10.1016/j.aap.2020.105575.

Edewaard, D.E., Fekety, D., Szubski, E., Tyrrell, R., Rosopa, P., 2017. The conspicuity benefits of dynamic and static bicycle taillights at night. Paper Presented at the *Human Factors and Ergonomics Society Annual Meeting* 1567–1568. https://doi.org/10.1177/1541931213601755.

Edewaard, D.E., Szubski, E., Tyrrell, R., Duchowski, A., 2019. The Conspicuity Benefits of Bicycle Taillights in Daylight. Paper Presented at the *Driving Assessment Conference* 370–376.

Fotios, S., Castleton, H.F., 2017. Lighting for cycling in the UK—A review. Lighting Research & Technology 49 (3), 381–395. https://doi.org/10.1177/1477153515609391.

Hancock, P.A., 2019. On the Dynamics of Conspicuity. Human Factors 61 (6), 857–865. https://doi.org/10.1177/0018720819840849.

Hepler, T.J., Feltz, D.L., 2012. Take the first heuristic, self-efficacy, and decision-making in sport. Journal of Experimental Psychology. Applied 18 (2), 154–161. https://doi.org/10.1037/a0027807.

Hepler, T. J. (2016). Can Self-efficacy Pave the Way for Successful Decision-making in Sport? *Journal of Sport Behavior, 39*(2), 147-159. https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=jlh&AN=115072574&site=ehost-live&scope=site&custid=s1123049.

Herslund, M., Jørgensen, N.O., 2003. Looked-but-failed-to-see-errors in traffic. Accident Analysis and Prevention 35 (6), 885–891. https://doi.org/10.1016/S0001-4575(02)00095-7.

Hsieh, M., Chen, L., Lee, Y., & Liu, Q. (2022). A Simulation-Based Study of the Effect of Brake Light Flashing Frequency on Driver Brake Behavior from the Perspective of Response Time. *Behavioral Sciences (2076-328X), 12*(9), 332. 10.3390/bs12090332.

Kawahara, J., Yanase, K., & Kitazaki, M. (2012). Attentional capture by the onset and offset of motion signals outside the spatial focus of attention. *Journal of Vision, 12* (12)10.1167/12.12.10.

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

Lahrmann, H., Madsen, T.K.O., Olesen, A.V., 2018. Randomized trials and self-reported accidents as a method to study safety-enhancing measures for cyclists—Two case studies. Accident Analysis and Prevention 114, 17–24. https://doi.org/10.1016/j.aap.2017.07.019.

Langham, M., Moberly, N., 2003. Pedestrian conspicuity research: a review. Ergonomics 46 (4), 345. https://doi.org/10.1080/0014013021000039574.

MacArthur, J., Harpool, M., Scheppke, D., 2019. How Technology Can Affect the Demand for Bicycle Transportation: The State of Technology and Projected Applications of Connected Bicycles, . National Institute for Transportation and Communities (NITC), Portland, OR.

Mackenzie, A.K., Harris, J.M., 2017. A link between attentional function, effective eye movements, and driving ability. Journal of Experimental Psychology: Human Perception and Performance 43 (2), 381. https://doi.org/10.1037/xhp0000297.

Madsen, J.C.O., Andersen, T., Lahrmann, H.S., 2013. Safety effects of permanent running lights for bicycles: A controlled experiment. Accident Analysis and Prevention 50, 820–829. https://doi.org/10.1016/j.aap.2012.07.006.

Møller, M., Janstrup, K.H., Pilegaard, N., 2021. Improving knowledge of cyclist crashes based on hospital data including crash descriptions from open text fields. Journal of Safety Research 76, 36–43. https://doi.org/10.1016/j.jsr.2020.11.004.

Moran, C., Bennett, J.M., Prabhakharan, P., 2019. Road user hazard perception tests: A systematic review of current methodologies. Accident Analysis & Prevention 129, 309–333.

OECD. (2001). Ageing and transport: Mobility needs and safety issues. Paris: Organisation for Economic Co-operation and Development. Retrieved from http://www.internat ionaltransportforum.org/Pub/pdf/01Ageing.pdf.

O'Hern, S., Oxley, J., 2018. Fatal cyclist crashes in Australia. Traffic Injury Prevention 19, S27–S31. https://doi.org/10.1080/15389588.2018.1497166.

Pearson, L., Berkovic, D., Reeder, S., Gabbe, B., Beck, B., 2023. Adults' self-reported barriers and enablers to riding a bike for transport: a systematic review. Transport Reviews 43 (3), 356–384. https://doi.org/10.1080/01441647.2022.2113570.

Prati, G., Marín Puchades, V., De Angelis, M., Fraboni, F., Pietrantoni, L., 2018. Factors contributing to bicycle–motorised vehicle collisions: a systematic literature review. Transport Reviews 38 (2), 184–208.

Rogé, J., Ndiaye, D., Aillerie, I., Aillerie, S., Navarro, J., Vienne, F., 2017. Mechanisms underlying cognitive conspicuity in the detection of cyclists by car drivers. Accident Analysis and Prevention 104, 88–95. https://doi.org/10.1016/j.aap.2017.04.006.

Rogé, J., Laurent, S., Ndiaye, D., Aillerie, I., Vienne, F., 2019. Does a yellow jacket enhance cyclists' sensory conspicuity for car drivers during daylight hours in an urban environment? Safety Science 119, 385–391. https://doi.org/10.1016/j.ssci.2018.06.023.

Salmon, P.M., Naughton, M., Hulme, A., McLean, S., 2022. Bicycle crash contributory factors: A systematic review. Safety Science 145, N.PAG. https://doi.org/10.1016/j.ssci.2021.105511.

Schoeberl, T., Fuchs, I., Theeuwes, J., Ansorge, U., 2015. Stimulus-driven attentional capture by subliminal onset cues. Attention, Perception, & Psychophysics 77 (3), 737–748. https://doi.org/10.3758/s13414-014-0802-4.

Stolte, M., Ansorge, U., 2021. Automatic capture of attention by flicker. Attention, Perception, & Psychophysics 83 (4), 1407–1415. https://doi.org/10.3758/s13414-020-02237-2.

Strayer, D.L., Johnston, W.A., 2000. Novel popout is an attention-based phenomenon: An ERP analysis. Perception & Psychophysics 62 (3), 459–470. https://doi.org/10.3758/BF03212098.

Thornley, S. J., Woodward, A., Langley, J. D., Ameratunga, S. N., & Rodgers, A. (2008). Conspicuity and bicycle crashes: preliminary findings of the Taupo Bicycle Study. *Injury Prevention (1353-8047), 14*(1), 11-18. https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=s3h&AN=31141924&site=ehost-live&scope=site&custid=s1123049.

Tin Tin, S., Woodward, A., Ameratunga, S., 2015. The role of conspicuity in preventing bicycle crashes involving a motor vehicle. European Journal of Public Health 25 (3), 517–522. https://doi.org/10.1093/eurpub/cku117.

Transport for London, 2014. Cycle Safety Action Plan, . Transport for London, London, UK.

Useche, S.A., Alonso, F., Montoro, L., Esteban, C., 2018. Distraction of cyclists: how does it influence their risky behaviors and traffic crashes? PeerJ 6, e5616.

Wood, G., Hartley, G., Furley, P.A., Wilson, M.R., 2016. Working memory capacity, visual attention and hazard perception in driving. Journal of Applied Research in Memory and Cognition 5 (4), 454–462. https://doi.org/10.1016/j.jarmac.2016.04.009.