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Testing of bicycle lighting: Method development and evaluation

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ABSTRACT

In darkness it is legally obligatory to light vehicles, both to enable their operators to see where they are travelling and to make the vehicle visible and recognisable to other road users. Legal requirements differ between vehicle types and, for bicycle lighting, also between countries. So far, in spite of some indications, there is no definite evidence of a relationship between crashes involving cyclists and darkness, nor on the presence of bicycle lighting and crash risk in darkness, possibly due to a lack of prevalence data. There are no standards for scientific or consumer testing of bicycle lights, and visibility-related results are inconclusive. Three test methods were employed to evaluate generic bicycle light features such as beam shape, brightness, steady versus flashing beam, and mounting position for their effects on seeing and being seen, while investigating which method was best suited for which type of evaluation. In static indoor laboratory testing, brightness was measured and beam shape documented photographically. In static outdoor testing, visibility from 300 m was evaluated, subjective ratings were collected, and beam shape documented. Three front-light beam types were then evaluated for their effect on gap acceptance in a dynamic setting in an urban environment, and subjective ratings were collected. All 18 tested lamps fulfilled the legal requirements, with a bright, steady front beam receiving the highest subjective ratings. Gap acceptance was influenced only by cyclist speed, but neither by beam type nor mounting position. To capture the effect of generic bicycle light features on perception, behaviour, and acceptance, one single method is not enough, and standardised laboratory tests should be combined with research-question–specific dynamic testing.

Introduction

To implement the 2030 Agenda for Sustainable Development there is a need to shift toward safer, cleaner, more energy-efficient, and affordable modes of transport generating higher levels of physical activity, such as cycling (Stockholm Declaration, 2020). Sweden, like many other countries, is struggling with the, in some cases, contradictory goals of increasing cycling while reducing the number of crashes resulting in injured cyclists (Regeringskansliet, 2017). To improve road safety, and for security and accessibility reasons, road lighting is important. Separate cycle paths in urban areas are, however, often perceived to have insufficient lighting (Niska, 2007), and road lighting is typically absent on rural roads. In such cases, a proper bicycle headlight is essential to illuminate road deficiencies or temporary objects putting cyclists at risk. In Sweden, eight out of ten severely injured cyclists admitted to hospital emergency wards have been injured in single-bicycle crashes largely related to road infrastructure (Niska, 2013).

In general, lighting a vehicle in darkness serves two purposes: to see and to be seen. In areas without sufficient external illumination, a headlight is necessary in order to see where one is going. A vehicle should also be visible and recognisable to other road users, which is an important precondition for smooth and safe interactions. For this purpose, lights and reflectors can be used. Here, the focus is solely on lights.

Seeing and being seen do not necessarily require the same type of light setup. To see, it is typically enough to illuminate the area in the direction of travel with a light source that is bright enough for the travel speed and covers the relevant area in front, whereas to be seen, the vehicle should be discernible from all angles from which it can be approached. It helps if the future trajectory of the vehicle can be predicted. It is an international standard to use white or, in some countries, yellow lights for the front and red lights for the rear (Economic Commission and for Europe - Inland Transport Committee, 1968). Rear lights have the purpose of supporting being seen, and for motor vehicles they are required to indicate braking by increasing the brightness of the rear lights. The arrangement of lights can also aid in recognising the type of vehicle. Cars usually have two lights in the front and two in the back, demarcating the outer edges of the vehicle, with a centre high-mount brake light. Trains have three

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front lights in the shape of a triangle. Bicycles are required to have at least one front light and one rear light in the darkness, but additional lights are typically not illegal. Otherwise, legal requirements for bicycle lighting vary from country to country (ADFC Allgemeiner Deutscher Fahrrad-Club, European Cyclists' Federation, & Fietsersbond NL, 2012), with Sweden, where this study was conducted, demanding lights that are clearly visible from 300 m in darkness, with only the rear light being permitted to flash if the frequency is at least 200 flashes per minute (Transportstyrelsen, 2009). It is not specified, however, under what circumstances the lights should be visible from 300 m, for example, whether this is in a completely dark environment or in an urban area with ambient lighting, and what "clearly" means. The distance of 300 m is not justified on theoretical grounds.

Consumer-oriented testing of bicycle lights usually aims to recommend specific products. Testing procedures vary between tests, addressing anything from durability to brightness. Here, however, we are interested in the generic features of lighting setups and their relationship to road user behaviour and acceptance.

Although it is notoriously difficult to obtain reliable figures on cyclist prevalence both for location and time of day, there are indications that crashes resulting in cyclist fatality are more frequent in darkness than in daylight (ADFC Allgemeiner Deutscher Fahrrad-Club et al., 2012; Cairney, 1998; Mazharul Hoque, 1990; Twisk & Reurings, 2013). Factors such as expecting a cyclist to be present and the driving speed being adequate for the conditions are likely to play a role (Rogé et al., 2017). Enhanced visibility and recognisability of the cyclist are presumably beneficial, although no clear evidence of a connection between bicycle lighting and traffic safety has been established so far, possibly due to a lack of pertinent data (ADFC Allgemeiner Deutscher Fahrrad-Club et al., 2012). Swedish Traffic Accident Data Acquisition (STRADA), which contains records from hospital emergency departments and the police, does not include any information on the use of bicycle lighting in crashes involving injured cyclists. However, by considering the time of the crash occurrence and defining "darkness" as the sun being 6 degrees below the horizon, Niska and Eriksson (2013) found that 20 per cent of single-bicycle crashes and 13 per cent of cyclists' collisions with another cyclist occurred during darkness. A large New Zealand study found that factors such as cycling in urban areas and in areas where cycling is less common increase crash risk, with visibility enhancements having no effect (Tin Tin, Woodward, & Ameratunga, 2013, 2014).

Most studies evaluating bicycle light visibility do not make a direct connection to crash occurrence. In a setting with static cyclists in a naturalistic environment, Cairney (1998) found that a flashing taillight could be seen from a great distance in both cluttered and dark environments. Also regarding headlights, a flashing mode was identified as more visible than its steady counterparts, but headlights were generally seen later than taillights, despite their higher luminosity. Like Cairney, Edewaard (2017) used cyclists on a stationary trainer, such that there was no movement relative to the background. She found that the different lighting setups were detected from similar distances, but that the ability to recognise a cyclist as such was influenced by the setup. In a situation with a long, straight approach distance, biomotion implemented by heel-mounted lights with a steady beam led to the earliest recognition when the cyclist was pedalling, followed by a seat-post mounted flashing light. The heel-mounted lights without pedalling motion and a steady seat post light led to later recognition of the cyclist as such. Neither of the studies investigated the ability to judge the distance to the cyclist.

Toet, Beintema, de Vries, van der Leden, and Alferdinck (2008) investigated conspicuity operationalised as the visual angle at which a bicycle light was detected in different situations and environments (see also Wertheim, 2010). Again, a static setting was used, which was justified by the difficulty of obtaining reliable measurements in dynamic settings. The authors concluded that the effect of flashing lights depended on the situation: flashing front lights improved conspicuity in urban environments, whereas a flashing rear light in rural environments led to diminished conspicuity when approached from behind. Further results include that brighter lights tend to increase the angle at which a light was recognised (however, this was in 2008 – today's lights can be much brighter, and it has yet to be determined whether this relationship has an upper bound), and that it did not matter for conspicuity whether the light was attached to the bicycle or the cyclist's clothing, as long as it was not covered or hidden due to posture variations. Lastly, it was found that conspicuity was influenced by how the lamp was mounted, with slanted or angled positioning diminishing conspicuity.

All the above-mentioned studies used stationary cyclists or stationary bicycle lights and most employed moving observers (usually in cars). The recognition distances and conspicuity angles can provide an indication as to what lighting setup might be superior, assuming that detection and recognition from farther away is better. However, there might be a threshold above which increased detection or recognition distances/angles do not improve conspicuity. This threshold might, for example, be related to the relative speed between two road users.

When it comes to the predictability of a cyclist's path, Walker and Brosnan (2007) found that drivers tend to seek out the cyclist's face to make eye contact. Their study was conducted using photographs taken in daylight as the stimulus material. It can be speculated that intention prediction based on eye contact must be more difficult in darkness. Westerhuis and de Waard (2017) used video material of a cyclist video recorded from behind for an online survey about intention prediction, finding that predictions were no better than chance. The participants also indicated what cue(s) they used for prediction. Depending on whether the cyclist was turning or going straight, the cues proved of varying value. Head movements were predictive of left turns, speed was predictive of going straight on, and for turning right, a change in speed was the best cue, even though not many people claimed to use it. Another video-based study with a viewpoint from slightly above an intersection corroborated this: head movements were associated with correct predictions of turns and speed with correct predictions of going straight on (Hemeren et al., 2014).

"Gap acceptance" has been used as a method to assess the potential effect of various factors in a setting with dynamic traffic and a usually static observer on the minimum time or distance gap that a person would accept in order to cross traffic or merge (e.g. Daganzo, 1981; Schleinitz, Petzoldt, & Gehlert, 2020; Yannis, Papadimitriou, & Theofilatos, 2013). Schleinitz and Petzoldt (2019) and Petzoldt, Schleinitz, Krems, and Gehlert (2017) used the method to investigate whether gap acceptance differed among e-bikes, conventional bikes, and scooters. The common denominator for the method is to estimate the smallest gap that could still be acceptably used in the investigated situation.

To sum up, regulations for bicycle lighting do not seem to be grounded in research, consumer tests for bicycle lights do not follow any standard procedures, there is no hard evidence demonstrating a link between different light setups and crash involvement, and scientific studies of different aspects of bicycle lights typically use stationary cyclists. So far there is no "go-to method" for the evaluation of bicycle lights and no list of important features to evaluate. A sound testing method that defines and discerns important bicycle light features would be valuable for manufacturers and retailers as a basis for consumer information and is also a prerequisite for judicious regulations concerning bicycle lighting.

This paper contributes to current knowledge by evaluating different bicycle light features and testing methods. Our aim is to compare different methods against each other using the same set (or subset) of lamps, focusing on their generic features. This is meant to be a first step in proposing a sound testing method for bicycle lights. For this reason, we also discuss generic aspects of lights in addition to the advantages and drawbacks of various testing methods. The investigated features are light intensity, beam shape, and whether the light is emitted continuously or in a flashing pattern. These features vary considerably between different lights on the market and could all affect the ability of cyclists to see or be seen. Mounting position is also considered, again, because of the variation that can be observed among cyclists. Light colour was not considered, as most modern headlights are white or very close to white.

Method

The methods for evaluating the lights were selected based on the following criteria: All methods had to be rather low in cost. One method should be based on objective measurements and not require any participants, for easy repeatability and widespread use. One method should test the Swedish regulation of visibility from 300 m. One method should involve a moving cyclist, as previous research has not considered this aspect. Comparability between methods should be achieved by using the same set or subset of bicycle lights.

Bicycle lights

Nine front and nine rear lights, some with multiple flash modes, were selected with the intention of covering a large range of prices and designs. All lights had LED lamps (state of the art at the time of testing), and all lights were battery powered except one front and one rear light designed to be powered by a hub dynamo, although a battery was used in the study. All lamps were new and bought specifically for the study. The prices ranged from below EUR 5 per front/rear pair to EUR 150 for the most expensive front light. A more detailed description of the lamps used in the study is available in Kircher and Niska (2020).

Lab test

The laboratory test was conducted to collect objective measurements of light intensity and beam shape. Lux measurements were taken in a large hall without any illumination except for an emergency-exit sign and the screen of a laptop computer. Each light was mounted 111 cm above the floor on a tripod such that the brightest central area of the light field, according to the visual judgement of two experimenters, was directed at a predefined point on a wall about 6 m away from the light at the same height.

For each light, measurements were taken using a hand-held lux meter at nine predefined points (Fig. 1) at a distance of 2 m from the lamp. The light fields of all tested lamps were symmetrical with respect to the vertical axis, which is why measurements were taken on the central axis and on the left-hand side. Measurements were only taken for modes with a steady beam, as the average incident light in flash mode depends on the percentage of time during which the light source is active. Ambient light measurements for the nine spots were taken and then subtracted from each measurement.

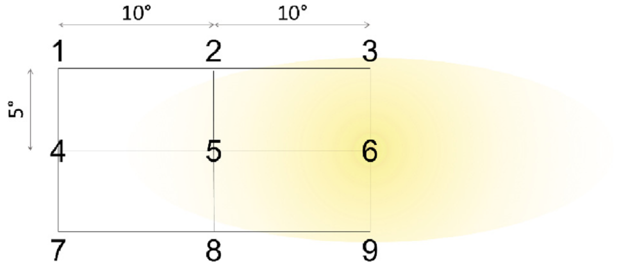


Fig. 1. Measurement pattern for the lux measurements. The visually defined brightest point of each light field was directed at point 6, located 111 cm above the floor (at the same height as the light).

Each steady beam setting was photographed against a white wall, with the light positioned on the same tripod and mounted 2 m from the wall. The camera settings were the same for all lamps (camera: Canon 5D MkIV; lens: Canon 24–70 mm f/2.8 set to 42 mm; aperture: f/2.8; shutter speed: 1/50 s; ISO 400).

Static field test

This study examined whether the lamps fulfil the Swedish legal requirement of being visible from at least 300 m. As the requirements specify neither ambient lighting nor whether adaptation to darkness is assumed, we used conditions that are easily replicable.

The bicycle lights were mounted on a rig at the same height from the ground. For front lights, the angle of the light was determined such that the road ahead was illuminated in the best possible way, as seen from a cyclist's point of view. If the light field was very homogeneous, the light was angled slightly downwards. Rear lights were positioned such that the centre of the light cone was parallel to the ground.

Six participants (three females) covering an age range of 15–69 years took part. Participants used the same vision correction as they would in traffic. The test was conducted on a 600-m-long straight section of a gravel road in darkness. The ambient light level was 0.01 lx. The participants were positioned 300 m from the rig. They stood close together, each with free view of the rig. Each participant judged whether a front, rear, or no light was shown, whether the beam was steady, flashing, or "rolling" (only rear lights, different LEDs illuminated at each point in time without any period with no illumination), and evaluated the different lights subjectively on a scale from 0 (completely unsatisfactory) to 10 (completely satisfactory). The participants could make written comments. Participants were asked not to discuss their ratings and impressions with one another.

The order in which the lights were illuminated was randomised, with different settings of the same lamp being treated as different cases. Altogether, 21 front and 21 rear light settings were shown. In three additional cases, no light was illuminated in order to ascertain that participants were not biased into saying that they saw a light. Each light setting was shown twice, such that within-subject consistency could be assessed.

For comparison with the beam shape photographs from the lab test, each front-light steady-beam setting was photographed (camera: Canon 5D MkIV; lens: Canon 24–70 mm f/2.8 set to 41 mm; aperture: f/2.8; shutter speed: 2 s; ISO 400) positioned as if mounted on the handlebars and seen from the cyclist's perspective. Reflectors and cones of white paper were placed along the road every 20 m to allow judgement of approximately how far the light beam reached.

Dynamic field test

The dynamic field test should link the objective measurements and subjective judgements of various bicycle light features to actual behaviour in a naturalistic traffic situation. Three of the front lights were selected based on the ratings from the static field test and presented a weak steady beam, a strong steady beam, and a flashing beam. Each light was used in two mounting positions, that is, on the handlebars and on the fork, and three approach speeds (i.e., 15, 20, and 25 km/h) were targeted per light setup. In addition, a no-light condition was included for all three speeds, resulting in 21 different setups per test block. The order of the approach setups was randomised. The gap acceptance paradigm was used, being a cost-effective test method including a moving cyclist, with the participants in the role of pedestrians intending to cross a street. The goal was to relate gap acceptance behaviour to the subjective perception of each setup in a realistic situation. The Swedish Ethical Review Authority judged that the study would not affect any ethically relevant aspects and therefore refrained from a full assessment (Dnr 2020–00643).

The study was conducted after nightfall in real traffic for high external validity. The location was an urban street leading up to an intersection with some street lighting and low traffic volumes in the evening (Fig. 2).

Twenty participants (nine females) with a mean age of 32.8 ± 10.2 years were recruited from a database of interested volunteers and by word of mouth. Tests were run with groups of two to four. The participants were informed of the purpose and procedure of the study and were given the opportunity to ask questions before signing an informed consent form. Participants were instructed to imagine that there was dense traffic on the road, and that they should indicate the minimum gap through which they would be willing to cross the road in front of an approaching cyclist by lifting a leg as if taking a step, or by extending an arm. The participants stood four metres apart at the roadside on the pavement. Distance markings in one-metre increments were sprayed on the curb for analytical purposes. Two practice trials were conducted before the actual data collection began, to ensure that the participants fully understood the procedures.

A camera (Garmin VIRB) mounted on the test bicycle video recorded the gap acceptance behaviour of each participant and logged the cyclist's speed via GPS. The cyclist experimenter, facing away from the participants, chose the upcoming lamp setting, turned around, and approached the participants from a distance of about 150 m, targeting the correct speed. The participants watched the cyclist and indicated their minimum accepted gap as described above. Upon doing this, the participants filled in an observer sheet, answering five questions about the light setup with ratings of between 0 and 10 (overall impression, glare, recognisable as bicycle, ease of judging speed, and ease of judging distance), after which the next trial was initiated. When one test block was finished, the participants switched places with one another, and a second block was run in the same way.

Demonstration

In addition to the lab and field tests, we conducted a series of smaller demonstrations using video recordings and photographs. These were mainly produced to illustrate effects that we, within the scope of this project, could not investigate in a more scientific manner, or for which a visual demonstration was sufficient to make a point. They consisted of:

1. Photographs of all included lamps from the side to illustrate visibility from the side *(reference to* Supplementary Material*)*.
2. Video recordings of steady beam versus various blinking modes for a selection of rear lamps, seen from the perspective of a following cyclist *(reference to* Supplementary Material*)*.
3. Video recording demonstrating how the mounting angle of a front light affects glare *(reference to* Supplementary Material*)*.
4. Video recording showing the visibility of reflectors worn by a walking pedestrian depending on where the lamp is mounted on the bicycle or cyclist *(reference to* Supplementary Material*)*.
5. Video recording showing the effect of biomotion *(reference to* Supplementary Material*)*.
6. Video recording demonstrating self-illumination using a front light turned towards the cyclist *(reference to* Supplementary Material*)*.

Analysis

The lab test results were not processed any further but were used as a descriptive basis in conjunction with the photographs. For the static field test, *t*-tests and one-way ANOVAs were used to compare different factors at an alpha level of 0.05.

For the dynamic field test, the video recording from the camera mounted on the handlebars was used to extract the gap acceptance distance for the different participants, based on the distance markings on the curb. Because of too low ISO settings and therefore unsatisfactory visibility on the video recording, the gap acceptance values for the first eight participants could not be coded. Thus, gap acceptance ratings are available for twelve participants and subjective ratings for 20 participants. For gap acceptance, the cyclist's actual speed was recorded when the cyclist was 30 m from the first participant, based on the measurement provided by the GPS built into the camera. Gap acceptance reactions at distances of more than 40 m could not be coded reliably, so those (9 out of 504 cases, i.e., 1.8%) were collectively set to 45 m.

Fig. 2. Study location of the dynamic field test.

Using the actual speed of the cyclist, the gap acceptance time in seconds was calculated. For inferential analyses of gap acceptance measures and subjective judgements, an alpha level of 0.05 was applied.

Results

Lab test

Lux readings in the brightest spot taken two metres from the light source varied from 0.9 to 1542 lx for front lights. Given that a lamp should not produce glare for oncoming road users, but at the same time the light must travel farther in the upper area of the beam, a light field with a sharp transition from bright to dark just above the brightest spot is desirable. The field closer to the bicycle should be illuminated as well, so a slow decrease in downwards luminosity is desirable. The intensity of each point in the upper and lower rows of measurement points relative to the brightest point was calculated.

With values at or below 0.01, the brighter lights tended to have a more distinct cutoff on the upper edge of the light field, and the three brightest lights, all above 800 lx at the brightest point, still delivered over 100 lx on average in the lower row of measurement points (see Table 1).

For rear lights, the range of eight of the nine lights was 0.2–3.6 lx, with one light being markedly brighter than all the others at 53.2 lx.

Static field test

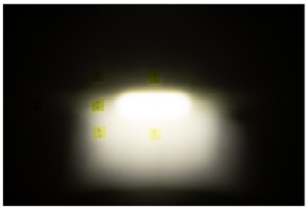
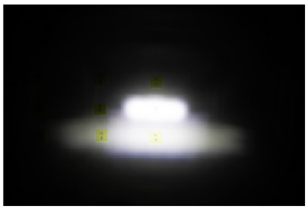
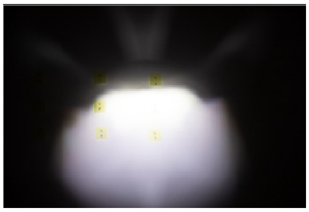
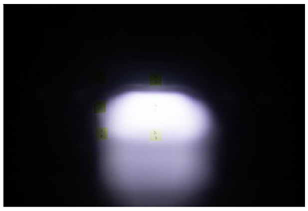
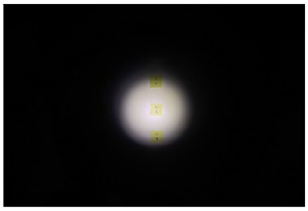
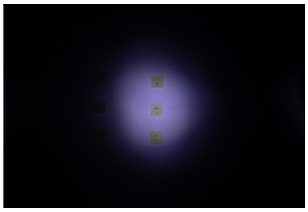
All participants could correctly identify all lights as being front or rear lights, and they all identified the occasions when no light was shown. Two participants missed one rating each. For front lights, out of a total of 256 ratings, 16 (6.3%) misclassifications were made regarding whether the beam was steady or flashing. In 13 cases, a flashing beam was mistaken for a rolling beam and in two cases a steady beam was mistaken for a rolling beam. For rear lights, out of a total of 252 classifications, 29 (11.5%) were misclassifications, with 12 cases in which a steady light was considered rolling and 10 cases in which a rolling light was considered flashing.

Overall, the correlation of the ratings in the first and second blocks was $r = 0.70$, with some variation between the six participants. The correlation of ratings for the youngest participant (aged 15 years) was non-significant at $r = 0.17$, with all other participants producing correlations of $r = 0.54–0.82$.

For front light settings, the mean ratings ranged from 4.2 to 8.0 on a scale of 0–10 (see Table 1 for steady beam ratings). No significant difference in ratings was found between settings with a steady beam (6.5 ± 2.0) and flash (6.3 ± 2.1) as per a one-way ANOVA ($F(1, 254) = 0.48$; $p = 0.49$). To put this into perspective, however, none of the four strongest lights had a flash mode, and for the five weakest lamps, the flash modes tended to receive slightly higher ratings than did the steady modes. Therefore, an additional one-way ANOVA was conducted that compared settings with a strong, steady beam (above 800 lx in the lab test), a weak steady beam, and a flashing beam. The analysis ($F(2, 481) = 7.1$; $p = .001$) and the Bonferroni-corrected post hoc comparisons showed that the strong steady beam received significantly higher ratings (7.2 ± 1.9) than did the flash setting (6.3 ± 2.1) or the weak steady beam (5.8 ± 1.9). As mentioned above, a representative of each of the three beam types was then selected for the dynamic field test.

For rear light settings, the mean ratings ranged from 3.4 to 7.2. As all lights except one were of similar luminosity, no distinction between strong or weak steady beams was made. A one-way ANOVA was used to compare the mean ratings for steady (5.4 ± 1.7), flashing (5.8 ± 1.8), and rolling (4.9 ± 1.9) modes, which showed that the

Table 1
Light field photographs against a white wall with measurement points marked. Per picture: 1st row: x = average lux of measurement points 1–3 divided by lux at point 6; 2nd row: lux measured at point 6 (distance 2 m), 3rd row: average subjective rating of steady beam in static field test; 4th row: average lux of measurement points 7–9. Colour shadings indicate desirability for good vision while preventing glare (green: desirable, yellow: medium, red: undesirable).

	0.005 1542 lx rating: 7.2 136 lx		0.01 862 lx rating 7.7 122 lx		0.01 832 lx rating: 6.7 191 lx
	0.01 683 lx rating: 7.4 58 lx		0.12 155 lx rating: 7.4 15 lx		0.17 62 lx rating 6.7 12 lx
	0.46 6 lx rating: 5.6 4 lx		1.0 3 lx rating: 5.4 3 lx		0.98 1 lx rating: 4.2 0.8 lx

flashing mode was rated significantly higher than was the rolling mode (F(2, 249) = 3.3; $p = 0.04$).

The lab photographs were compared with the photographs taken in the field (for two examples, see Table 2), showing how the light field seen against a vertical wall compares with the light distribution along a road in front of the lamp. The beam of the four lamps brighter than 500 lx had a reach of around 60 m or more.

Dynamic field test

For each block, 420 subjective ratings (20 participants × 21 setups) and 252 gap acceptance values were available. Intra-rater reliability was investigated using Pearson's correlation. For the subjective ratings, values ranged from $r = 0.62$ (ease of estimating speed) to 0.75 (general rating of setup), with all correlations being highly significant ($p < 0.001$). For gap acceptance in metres, the correlation coefficient was $r = 0.52$ ($p < 0.001$), and for gap acceptance in seconds, calculated using the actual speed of the cyclist, it was $r = 0.54$ ($p < 0.001$). Spontaneous comments by several participants indicated that they experienced the ambient light coming from a street light as affecting their ratings, as two of the positions were brighter than the other two positions. Therefore, the factor "ambient light" was included in the analyses.

A multivariate analysis of the five rating variables and the two gap acceptance variables using the main effects of the factors "block", "gender", and "ambient light" was conducted to investigate the possible general influences of external factors. Only "gender" had a main effect (Wilk's lambda F(7, 494) = 4.6, $p < 0.001$). Specifically, women gave slightly higher ratings overall on the question of whether the lighting setup looked as if there was a bicycle (F(1, 497) = 5.4, $p = 0.02$). The minimum accepted gaps were on average larger (F(1, 479) = 12.9, $p < 0.001$) for women (22.9 m) than for men (20.8 m), which was also noticeable in the accepted time gaps (F(1, 479) = 12.2, $p = 0.001$; women: 4.2 s, men: 3.8 s).

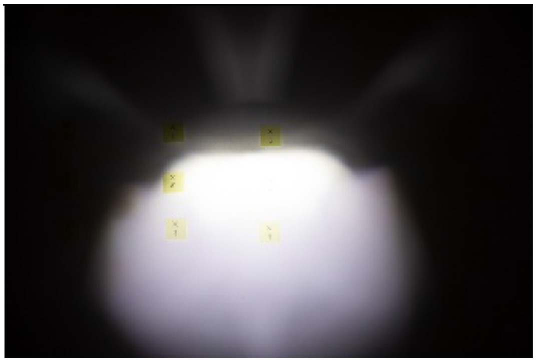
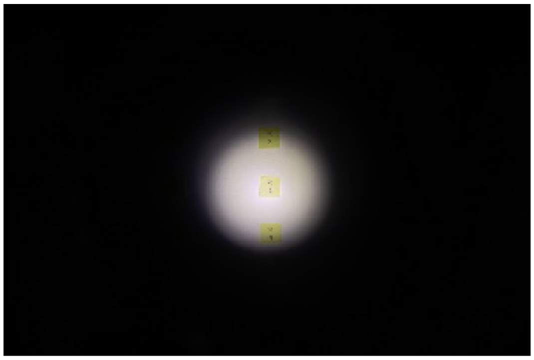
Another multivariate analysis of the same dependent variables was conducted, but using the systematically varied factors "beam", "mounting", and "speed", considering main effects and two-way interactions. No interaction effects with "speed" were found, but all other effects were statistically significant for at least some of the variables.

Glare was perceived to be highest for the flashing light mounted on the fork (F(2, 487) = 18.9, $p < .001$; rating 6.6/10 with all other combinations below 4/10). The same setting also produced the largest gap acceptance values (F(2, 487) = 4.4, $p = 0.013$; time gap: 4.4 s with all other combinations around 4 s or below and comparable results for distance gaps).

The factor "beam" had a significant main effect on all five rating variables (Wilk's lambda F(14, 962) = 14.7, $p < 0.001$). The setup with no light typically differed the most from all other setups, in that its general impression was the worst (1.2/10, all others above 5/10): it reportedly looked the least like a bicycle (3.3/10, all others above 6/10), was perceived to be least suitable for estimating speed and distance (around 3.5/10, all others above 5.5/10), but, understandably, did not produce any glare (0/10, all others above 2.5/10). Apart from the presented interaction effects, the strong steady beam was rated the highest (7.2), followed by the weak steady beam (6.2) and then the flashing beam (5.4), all significantly different from one another. The same order applied to the property of signifying a bicycle, with ratings always around 0.5 points higher for handlebar-mounted lights, but with a non-significant difference between strong steady and weak steady beams. The beams were rated in the same order for speed and distance estimation, and again, the difference between the two steady beams was non-significant. The factor "beam" did not significantly affect gap acceptance.

Mounting the light on the handlebars led to significantly more positive ratings overall for general impression, perceived glare, and the

Table 2
Demonstration of how the light field of the same lamp looks against a white wall and on a road. The brighter field on the upper edge for the brighter lamp results in uniform illumination of the roadway.

	Against white wall, distance 2 *m*	On gravel road in darkness
832 lx 60–80-m beam		
155 lx <20-m beam		

ability to look like a bicycle, but did not significantly affect the perceived ability to estimate speed or distance and did not have any significant effect on gap acceptance.

The cyclist's speed did not significantly influence any of the five subjective ratings, but had an impact on gap acceptance. With each increase of 5 km/h in (target) speed, the accepted gap increased by 2.8 m, going from 19.1 m at 15 km/h to 24.7 m at 25 km/h (F(2, 487) = 26.7, $p < 0.001$). Translated into time, this means that with each increase of 5 km/h in (target) speed, the accepted time gap decreased by approximately 0.6 s, going from 4.7 s at 15 km/h to 3.3 s at 25 km/h.

Demonstrations

We assume that it is beneficial if bicycle lights can be seen clearly from the side, and if they show the same colour (white/yellow for front and red for rear) to the side as in their main direction. Some of the tested lights did not fulfil these requirements *(reference to* Supplementary Material*)*. It appears likely that steady rear lights are experienced as less irritating for following traffic, and that distance and speed judgements are easier to make for steady lights, especially for groups of cyclists *(reference to* Supplementary Material*)*. Mounting position is assumed to influence glare more than does type of light *(reference to* Supplementary Material*)*. A light close to the line of sight is necessary to exploit the retroreflective qualities of a reflector *(reference to* Supplementary Material*)*. On the other hand, though this was not demonstrated or tested here, a light close to the line of sight eliminates shadows that could otherwise indicate edges and holes. Biomotion is assumed to increase recognition and intention prediction *(reference to* Supplementary Material*)*, as also indicated by Hemeren, Johannesson, Lebram, and Eriksson (2017). The final demonstration *(reference to* Supplementary Material*)* indicated that, at least with light-coloured clothing, a steady light directed towards the cyclist may improve cyclist recognisability, even though the biomotion setup may be more compelling. The setup with the rearward-facing lamp was inspired by mobile phone screens illuminating pedestrians' faces in darkness.

Discussion

Of the options tested here and based on the cumulative results, the best light setup for both seeing and being seen appears to be a strong steady beam whose light field is cut off sharply on the upper edge, but flares out to the sides on the lower edge. It should be mounted on the handlebars for better recognition and pointed slightly downwards to avoid glare. The subjective ratings in both field tests combined with the optical impression from the photographs in the lab and the static field test are the main sources for this judgement.

Exactly how far the light beam should extend was not investigated here and likely depends on how dark it is, how fast the cyclist is travelling, and how predictable the path is. Lab-style measurements of emergency braking distances with different bicycles and with riders of different experience levels showed that the "worst case" – a speed of 30 km/h on a wet road surface – generated stopping distances of below 15 m (Aderum et al., 2019). All of the studied lights with a strong beam lit up a field of around four times that distance, which means that at 30 km/h, the distance travelled in the upcoming 7 s is illuminated. This can be assumed to be experienced as comfortable in most situations.

The participants in the static and the dynamic field tests agreed on rating the strong steady front beam the highest. However, in the static field test, subjective ratings from a distance of 300 m were higher for flashing lights than for weak steady beams, whereas it was the opposite in the more realistic traffic situation in the dynamic field test. Presumably, the flashing light was not experienced as irritating when seen from a longer distance, whereas at closer distances it was perceived as irritating and producing glare. The weak steady beam, on the other hand, might have appeared too weak from the longer distance, but still sufficient in the urban setting.

Flashing rear lights were preferred when viewed from 300 m (see also Edewaard, 2017, who found that flashing lights were more conspicuous than steady beams when approached from afar). Unfortunately, we had no opportunity to study flashing versus steady beams from a closer distance, in a dynamic setting, and for groups of cyclists, except for the visual demonstrations. A systematic evaluation of these factors is recommended as a next step.

It turned out that the behavioural data on gap acceptance did not reflect the participants' ratings. Regardless of the light setting, gap acceptance was mainly influenced by the distance of the cyclist from the participant without full compensation for speed, as shown by the shorter time gaps at higher speeds. Several previous studies using various configurations of interacting road users obtained similar results (Connelly, Conaglen, Parsonson, & Isler, 1998; Hunt, Harper, & Lie, 2011; Oxley, Ihsen, Fildes, Charlton, & Day, 2005; Parsonson, Isler, & Hansson, 1999; Simpson, Johnston, & Richardson, 2003). From a safety point of view, at least constant time gaps and therefore larger distance gaps are desirable at higher speeds, assuming that the aim is to keep the post-encroachment time constant (van der Horst, de Goede, de Hair-Buijssen, & Methorst, 2014).

Even though the participants reported differences between the setups in supporting speed and distance judgements, this did not affect their actual behaviour. Thus, based on the gap acceptance results, it does not really make a difference with which light setup the bicycle is equipped, but to increase a positive perception of the cyclist, the setting recommended above is still the most suitable.

The three different methodological approaches yielded different types of results. The lab test is fast and simple to set up and conduct and yields sufficient information to assess whether a light is suitable for seeing with it in the dark, and whether it is likely to produce glare. The static field test contributed a specific answer to the research question about the Swedish visibility regulation. It showed that all tested types of lights, even the smallest and weakest in the study, were visible and recognisable as front or rear lights from a distance of 300 m in practically complete darkness. This could give rise to the assumption that any bicycle light would pass this test. The photographs in the field helped in translating the pictures taken in the lab to a field setting. They could be used for illustrative purposes, such that for future tests, an assessment of the light beam shape in the lab would be sufficient.

The subjective ratings in the two field studies were only partially consistent, and the judgements made in the more realistic setting involving close interaction with the cyclist should be prioritised. Interestingly, the participants' behaviour and subjective ratings did not yield redundant data, showing that a rating cannot be taken at face value regarding the resulting behaviour. The dynamic field test investigated only one type of interaction with a cyclist, which limits the possibilities to generalise. Systematic studies of different interaction types could supply converging evidence about which bicycle lighting setup is most successful for visibility, conspicuity, recognisability, and appropriate actions. Whether and how this can then be related to crash involvement is yet another step.

With respect to methods, we would argue that standardised lab testing, possibly in conjunction with a field study in a realistic setting to investigate a specific question, is the most promising way to go. The static field study delivered information relevant to the specific question of Swedish law compliance, but did not provide any added value. Tests with two dynamic parts are complicated and resource intensive to set up and control, so they may be more appropriate for demonstrations than systematic testing.

The demonstrations conducted here showcase some of the topics that merit further study regarding both cyclist visibility and helping the cyclist see. Interactions with other road users, including being overtaken by faster vehicles or situations where paths cross at intersections or in shared environments, are diverse and numerous. It may be meaningful to include investigations into how retroreflective material can be used to complement or enhance bicycle lights. Here, biomotion and its potential for intention prediction especially holds promise (Fylan et al., 2020; Hemeren et al., 2017; Kwan & Mapstone, 2004). Given the differences in foveal and peripheral vision (Rosenholtz, 2016; Wolfe, Dobres, Rosenholtz, & Reimer, 2017), it is also important to investigate whether there are any light settings that are particularly useful for detection with peripheral vision, as cyclist infrastructure is often located outside the forward field of view.

The fact that retroreflective material reflects light back to its source was clearly shown in the demonstration of the mounting position of the light. The farther away from the cyclist's eyes the lamp is mounted, the more difficult it becomes for the cyclist to see traffic signs, road-construction–related information, and other retroreflective targets. For the specific purpose of seeing retroreflective material, a headlamp would be best, but this is typically not legal, at least as the only light source used, and in some countries the maximum allowed mounting height is limited.

While the study aimed at investigating generic features of bicycle lights, those still had to be represented by actual bicycle lamps. The selection of prototypes was intended to include a wide range of lamps, but it is still possible that the selection was biased. Features such as build, handling, price, robustness, and charging time were not tested at all, but play major roles for the end user, and these matters could be investigated in consumer testing.

Conclusions

This study complemented the existing literature by conducting a dynamic test in a real-world environment, and by combining lab results with field testing. Based on the current findings in conjunction with previous results, for a front bicycle light intended to be used as a seeing aid in an unlit environment, we recommend a steady beam of at least 500 lx measured in the brightest spot 2 m away from the light source. It should have a beam shape that illuminates the road evenly, including the sides, without producing glare for other road users. The variation in luminosity was smaller for rear lights and no dynamic testing was conducted for the flash mode. We recommend investigations in urban and rural settings with both one and several cyclists. It is likely that there is no single best light for all purposes, so specific testing could make valuable contributions for different types of cyclists and situations.

For testing, we recommend laboratory tests under easily repeatable conditions to allow for reliable comparisons, in combination with research-question–specific field tests in real environments for high external validity. A standardised laboratory procedure that at least assesses illuminance at several significant points and visualises beam shape, possibly adding handling-related criteria, could be developed. The relevance of these objective factors to specific research questions could then be evaluated in context-sensitive field tests.

CRediT authorship contribution statement

Katja Kircher: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Anna Niska:** Conceptualization, Investigation, Resources, Project administration, Writing - original draft, Writing - review & editing, Funding acquisition.

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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Appendix A. Supplementary data

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