HEADLAMPS FOR WORKING OUTDOORS IN THE DARK

Bieske, K.[1], Vandahl, C.[1], Hubalek, S.[2], Schierz, C.[1]
[1] Technische Universität Ilmenau, Germany, [2] Social Accident Insurance for the Energy, Textile, Electrical and Media Products Sectors (BG ETEM), Germany
karin.bieske@tu-ilmenau.de

Abstract

The lighting requirements for headlamps should be ideally defined, to ensure good vision and to avoid accidents in the dark: (1) Headlamps should have several different lighting modes for allowing to adapt the light output and the light distribution according to different visual tasks and operation purposes. (2) Vision within the entire visual field can be achieved with a “low gradient” effect from the light cone towards the dark surrounding. (3) Headlamps have to be flicker-free. (4) The risk of direct and indirect glare must be reduced.

Therefore, when designing a headlamp, a compromise has to be found between the requirements for luminous flux, luminous intensity distribution and handling, whereas glare and disturbances of dark adaptation need to be avoided.

We would like to suggest additional standardization on top of the existing ANSI standard. This should also be beneficial when using headlamps in brighter environments and for the use of pocket lamps.

Keywords: Headlamp, Outdoor, Darkness, Standardization, Glare, Visual Field, Flicker

1 Motivation

Working in the dark requires good lighting to enable people to see properly. Whereas lighting can often be stationary, there are workstations, e.g. at construction sites for railway tracks and catenary, where lighting needs to be more flexible and therefore mobile. Maximum flexibility is required during the night when climbing up a catenary mast for troubleshooting and repairs in the rail network. Since there are catenary wires near the workers and both hands are needed when climbing and working, headlamps are the only lighting solution.

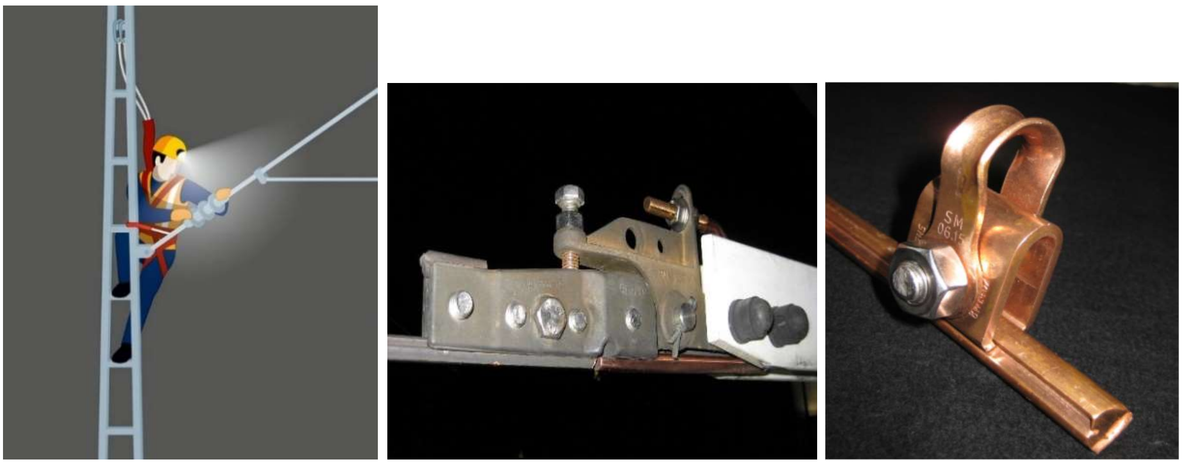

Figure 1 – Left: Working on a catenary mast in the dark. Middle and right: Typical materials used, some reflect strongly when new and, thus, can cause strong glare by reflection.

As the usage of headlamps as a single light source, is against existing German law requirements (BMAS 2023), BG ETEM launched a research project with the Ilmenau University of Technology to define meaningful minimum standards for those lighting devices. The ANSI standard (ANSI 2019) was a first approach for describing necessary requirements for headlamps, but soon turned out not to be detailed enough.

Another challenge arises, from the prevailing competition among the manufacturers of headlamps to produce only the brightest possible headlamps. However, this approach contradicts the needs of dark-adapted eyes, which require the ability to orient themselves in dark surroundings. It is important to consider the potential for glare caused by glossy workpieces, tools, and especially the headlamps of colleagues working nearby, as this can result in visual impairment. Particularly when climbing a mast and working in an environment with electrical hazards, impairment of vision caused by glare can be very critical and poses a risk potentially resulting in severe accidents.

2 Vision in dark surroundings

Enabling night-time vision in unlit areas is an especially difficult task. Illuminance is about 0,1 lx to 2 lx (with full moon). To ensure that there are no disturbances within the field of vision, the contrast between the visual object within the light cone and the unlit environment should be ideally 10:1 up to a maximum of 100:1 (Bodmann 1962). Thus, the illuminance in the middle of the light cone should be in between 1 lx to 10 lx up to 20 lx to 200 lx – presuming a similar reflectance. A sharp light cone hinders peripheral view, since little differences in brightness can no longer be perceived on the periphery of the visual field. To achieve a smooth transition between the illuminance in the middle and at the boundary of the light cone, a ratio of 3:1 is recommended.

The human eye can adapt to a large range of illumination levels. However, compared to vision in bright environments, vision in dark environments typically results in lower visual acuity, reduced contrast sensitivity, increased sensitivity to glare, and limited colour vision. It takes several minutes for the eye to fully adapt from a bright environment to a dark one. Adaption to a bright environment, on the other hand, takes only 5 seconds. When the light in the central field of vision becomes too bright, the ability to discern lower contrasts in the darker periphery is compromised. Additionally, light sources cause significantly more glare in dark surroundings as compared to bright environments. This adversely affects vision and, consequently, has a negative impact on safety.

3 Method

The lighting of headlamps should be ideally designed, to ensure good vision and to avoid accidents. For this purpose, lighting requirements must be defined. To gather the relevant data, we proceeded as follows: Carrying out a (1) field analysis, we gathered relevant tasks including operation details and purposes and defined typical viewing distances and other visual factors. We simulated these factors in a (2) laboratory study. Thus, we were able to define relevant parameters for a suitable headlamp like illuminance, light distribution, light beam width, luminous flux, requirements for a low gradient and the avoidance of excessive glare. Based on these parameters, (3) commercially available headlamps were measured in the light laboratory and assessed. Unfortunately, no headlamp currently available, could meet these standards. Therefore, (4) in cooperation with a headlamp manufacturer, prototypes, based on an available headlamp, were built. Those prototypes were tested by railway workers in a (5) field study. (6) Additionally, a new standard was conceived and published.

3.1 Field analysis

An appropriate headlamp must be chosen depending on the particular tasks and operating conditions. After initial theoretical considerations on working in the dark, we analysed operation purposes, activities, and visual conditions at several different construction sites. We identified three different tasks, each with its respective operational purposes. Viewing distances and field of view widths were defined according to the different operation purposes. Table 1 shows an overview.

Table 1 – Viewing distance and field of view width according to different operation purposes.

No.	Task/operation purpose	Viewing distance	Field of view width
1	Working within the handle area	0,5 m	0,7 m (± 35°)
2	Walking on railway tracks and orientation in the track bed	3 m to 5 m	Track gauge: 1,5 m (± 15°) Track bed: 2,4 m (± 15°)
3	Fixation of grounding rods	up to 10 m	1 m (± 2,5°)

At the same time, we inquired about headlamps, which are used for up to 8 hours during a shift for troubleshooting in the rail network in unlit surroundings. Some of the problems with headlamps are shown in Figure 2. Left: Sharply defined, brightly illuminated areas, which means that vision is only possible in the lit area, but not outside. Additionally, the light cone is rather narrow. Middle: Inhomogeneous lighting with relevant risk of - direct and indirect - disability glare due to the extremely bright inner spot with a very small beam angle. Right: Image of the spatial luminance distribution of the light-emitting surface of a headlamp. The luminance in the yellow region is around 10^6 cd·m^{-2} up to $4·10^6$ cd·m^{-2} in the centre. This means that, looking straight into the headlamp as well as looking into glossy materials or tools reflecting the light can cause glare leading to vision impairment and, thus, is a risk factor.

Figure 2 – Examples of headlamps with potential for optimisation

Based on the knowledge gathered during the field analysis, a laboratory study was designed.

3.2 Laboratory study

When looking for subjects, we excluded younger persons due to the following reasons: older persons (a) need more light for achieving comparable vision and (b) are more sensitive to glare. The study was conducted with 22 male subjects (40 – 75 years, Mean value: 45 years, SD: 5 years). All of them were experienced in the use of headlamps and had normal vision.

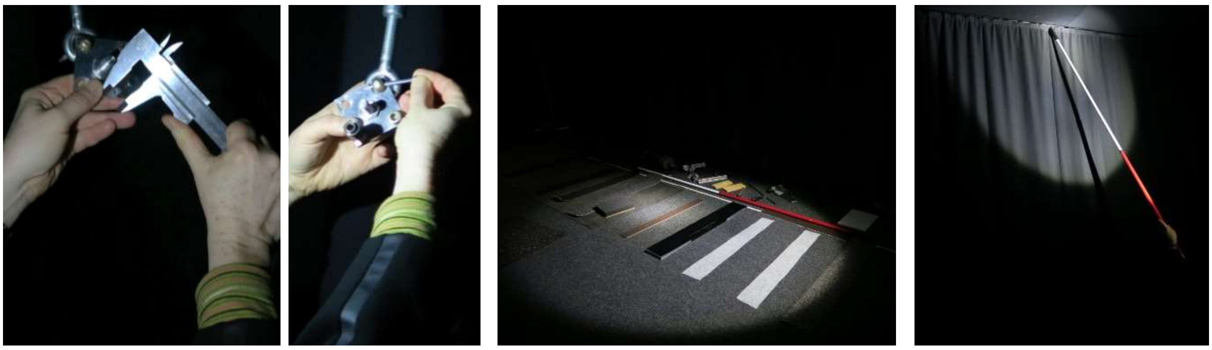

Figure 3 – Different tasks set-up in the laboratory study: Left: Working with glossy materials within the handle area. Middle: Walking on the railway tracks and orientation in the track bed with different reflectances. Right: Fixation of grounding rods in the height.

The set-up was as follows: The room was completely darkened, using light-absorbing black cloths. The size of the room was 4 m in width, 6 m in length and 2,8 m in height. Inside the room, the tasks shown in Figure 3 were executed.

A three-part laboratory study was conducted under conditions like those in practice to test the theoretical approaches. The following aspects were investigated: (i) individual settings of illuminance and the size of the light beam, (ii) evaluation of predefined light settings for different activities and (iii) an evaluation of direct glare and contrast vision (see section 3.2.3).

To define minimum requirements for individual settings, (i) a dimmable headlamp with a variable focus was used. The size of the light beam could be adjusted between ± 6° and ± 27° and additionally, the illuminance in the centre of the light beam at a measuring distance of 0,5 m towards to the luminaire could be varied between 26 lx and 450 lx. All subjects were asked to choose an individual lighting setting, which was at least sufficient for performing their work in the handle area and a second setting for walking on uneven terrain. Furthermore, glare caused by the chosen setting was evaluated when our subjects looked into a mirror, simulating a straight view into someone else's headlamp during an encounter situation.

For the evaluation of predefined light settings (ii), we modified a commercially available headlamp with optically clear and diffuse filters and filter combinations. In total, we realized eight lighting situations, each one designed for typical works in the handle area, and for walking in the track bed. Light cone sizes ranging from ± 25° to ± 50° (beam angle width) and illuminance levels between 5 lx and 270 lx (measuring distance: 0,5 m in the centre of the light beam towards to the luminaire) were tested. The glare of the respective lighting situation was assessed for each test situation by looking directly into a mirror. The maximum luminance levels were between 10^4 cd·m^{-2} and 1,2·10^6 cd·m^{-2}.

3.2.1 Working within the handle area

Illuminance and beam angle width: With the individually adjustable headlamp our subjects chose an illuminance of 65 lx on average (median: 45 lx) in a range between 15 lx and 177 lx (Figure 4 right). Regarding the width of the viewing area, they adjusted the angle between ± 17,5° and ± 27,5°. A beam angle of at least ± 25° was considered necessary.

Regarding the predefined light settings, the best evaluation was given to a headlamp with an illuminance of 25 lx and a large light cone of ± 35° to ± 50° (Figure 4 left). For the mounting and measuring tasks simulated, this level of illuminance is sufficient, considering the lack of disturbing glare. Headlamps with a higher illuminance were criticized for causing excessive glare. A wide beam angle makes it possible to cover the entire working area without any additional adjustment and head movement and enables vision in the periphery.

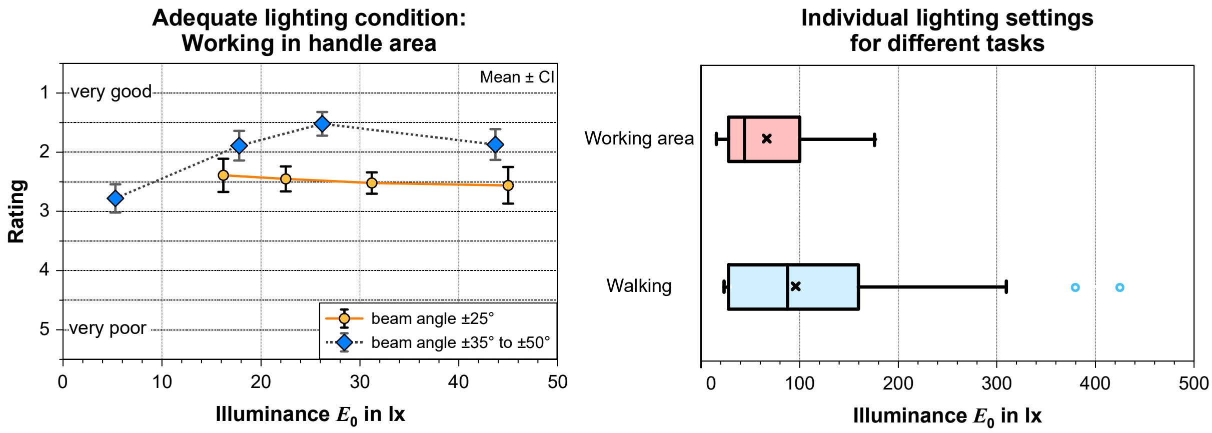

Figure 4 – Left: Overall assessment of the given lighting situations for working in the handle area (N = 22). Right: Boxplot of individual illuminance settings for different tasks (N = 22).

Glare: For the selected settings the glare rating ranged between 2 (not yet annoying) up to 5 (inacceptable) with an average rating of 3,3. Using a diffuser on the luminaire head results in a wide beam angle and prevents direct view into the LED light source. The diffuser reduces the maximum luminance of the light emitting surface and thus, the disturbing glare effect. With the LED chip visible, the glare effect was rated at least one level more critical.

3.2.2 Walking on railway tracks and orientation in the track bed

Illuminance and beam angle width: For detecting obstacles and irregularities when walking, the subjects selected an average of 125 lx (median: 90 lx), which is a double the illuminance compared to the illuminance for working in the handle area (Figure 4 right). 16 subjects selected a beam angle of ± 25°, 6 test persons were content with beam angles between ± 15° and ± 20°. Regarding glare the results were similar to the results mentioned beforehand.

In addition, the beam centre distance (distance between the person's location and the centre of the beam angle on the path) was determined. The result was between 0,6 m and 3,4 m with a mean value of 1,6 ± 0,7 m. This means, that many of the test persons looked straight ahead in a distance between 1 m and 2 m (which corresponds to a viewing distance of 2 m to 3 m) to avoid tripping, stumbling, and falling.

The best ratings for the predefined light settings were given to headlamps with an illuminance of 40 lx or more and with a large light beam of ± 35° to ± 50°. In contrast to a focused light distribution, a smooth, non-abrupt transition of the light distribution from the light beam to darkness (low gradient) was considered important, as this enables seeing the periphery and grasping the overall situation. A large field of vision was rated by the subjects as being pleasant. For spatial vision, it is beneficial if the light is aimed at a specific direction. Since the light beam is projected on the ground when walking, a shift of the light centre to the upper third is useful. This results in a higher uniformity of illuminance due to the light cone falling obliquely on the ground (Figure 3 middle).

3.2.3 Glare depending on the size of the light emitting area

We used light sources in three different sizes as shown in Figure 5 (from left to right: 1 cm x 1 cm, 3 cm x 7 cm and 5 cm x 9 cm). The illuminances measured at the eye were similar. Thus, the luminance of the light emitting areas decreased with increasing area size. The perception of glare rating ranged from 0 to 5 (0 = imperceptible, 1 = perceptible, 2 = not yet annoying, 3 = slightly annoying, 4 = annoying, 5 = unacceptable). Additionally, the contrast between the 3 x 9 fields located above the light source and having different levels of brightness had to be rated.

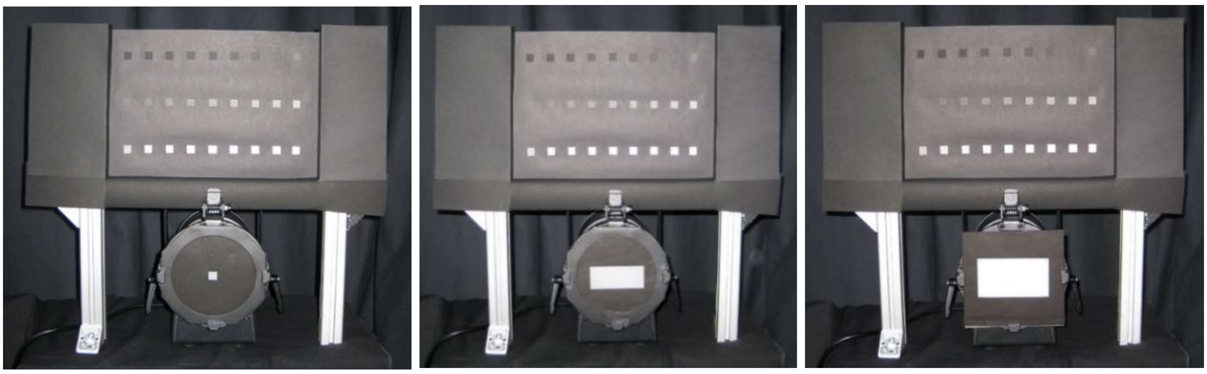

Figure 5 – Test setup for the rating of glare, dependent on the size of the light emitting area. Bottom left to right: increasing size of the light emitting area. The fields on top were used for fixating the viewing direction while estimating the contrast perception.

Figure 6 shows an increase of glare with (a) increase of luminance and (b) decrease of the light emitting area. Additionally, the test results show, that (c) the perception of low contrasts decreases with increasing luminance. The whole results of the laboratory study are documented in detail in (Bieske 2018).

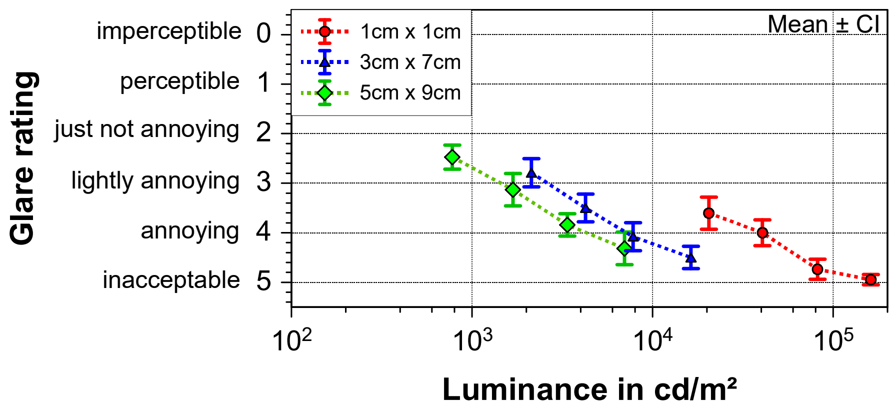

Figure 6 – Glare rating depending on luminance for different sizes of the light emitting area.

3.3 Prototyping

Based on the results of the laboratory study, minimum requirements were defined. With these parameters we looked for an appropriate headlamp on the market – without success. Therefore, we tried to rouse interest among manufacturers of headlamps situated in Germany, to develop a new prototype. Unfortunately, it was not possible to fund a completely newly developed headlamp. Fortunately, one manufacturing company was found, which modified some of its existing headlamps according to our requirements. Developed for rough environments, the headlamps already met all the requirements regarding robustness, handling with gloves, operability at low temperatures, etc. After modification of the lighting parameters the prototypes were measured in our light laboratory and tested outdoors in dark surroundings.

The tests revealed the necessity for optimising the design of the optical components to align the luminous intensity distribution and maximum luminance with our recommendations. In the case of rapid movements in the field of view – as it can for example occur during assembly work or during light rain – disturbing stroboscopic effects were observed. Therefore, for the enhanced prototypes, it was recommended to dim with constant current for adjusting the luminous flux of the luminaire instead of using pulse width modulation. Unfortunately, our requirements for maximum luminance could not be achieved with the modified prototype, so that we had to accept 200 000 cd·m^{-2} and more as a compromise. Table 2 shows the photometric parameters of the modified headlamp, which is depicted in Figure 7 on the right.

Table 2 – The parameters of the prototype. Illuminance E_0 is measured in the centre of the light beam at a distance of 0,5 m towards to the luminaire and I_0 is the corresponding luminous intensity

Task	Beam angle width	Illuminance E_0	Luminous intensity I_0	Total luminous flux Φ	max. luminance L (mean value)
Working within the handle area	± 26° (E_0/3) ± 39° (E_0/10)	56 lx	14,0 cd	16,9 lm	284 000 cd·m^{-2} (38 300 cd·m^{-2})
Walking	± 23,5° (E_0/3) ± 36,5° (E_0/10)	82 lx	20,4 cd	19,4 lm	202 900 cd·m^{-2} (60 570 cd·m^{-2})
Fixation of grounding rods (boost)	± 26° (E_0/3) ± 38° (E_0/10)	325 lx	81,2 cd	83,4 lm	674 000 cd·m^{-2} (142 600 cd·m^{-2})

3.4 Field study

The prototype was subsequently tested in the field. 19 test persons (27 to 61 years, mean value: 42 years, SD: 11 years) in three user companies used the luminaire in a work context during several night shifts. The evaluation was conducted at various locations with differing local and weather conditions, and while performing different tasks. In the experimental routine, it was not possible to accompany all test subjects and record the judgements individually. Therefore, the test persons gave their judgements in a questionnaire. The findings are documented in detail in (Bieske 2019).

The test luminaires were generally rated as well suited for the purposes of walking and working in the handle area. Only the "boost" mode to be used for the fixation of grounding rods was criticised (Figure 7 left). However, greater brightness and a bigger width of the light beam were desired.

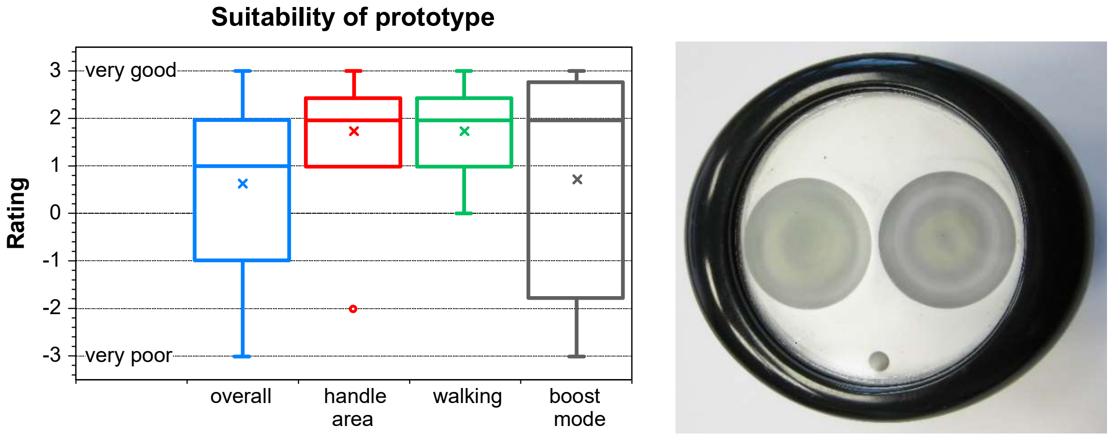

Figure 7 – Suitability of the different light modes of the prototype. Left: Boxplots of the subjective suitability ratings. Right: Picture of the prototype.

Based on the evaluation results, we are convinced that our prototype offers a practical solution for working outdoors in the dark. If conducting any future evaluation of a prototype, we would insist on personally instructing all workers to ensure that everyone understands the purposes, ideas, and the fact, that it takes some time, for the eyes to adapt to darkness. Additionally, we would try to ensure that the headlamps are exclusively used for outdoor work in dark surroundings.

The evaluation under practical conditions revealed that the results of the laboratory study are only partially accepted in practice. In most cases, even the higher illuminance of the test luminaire was perceived as insufficiently bright compared to the findings of the laboratory study. Therefore, it is proposed to double the lighting level for the mode "working in the handle area" and to triple the lighting level for the mode "walking" compared to the results of the initial laboratory study. This compromise is also justified by the fact that headlamps are often not exclusively used in complete darkness.

3.5 Implementation

Based on the study we published several articles in German health and safety journals and a special publication called "Fachbereich AKTUELL", which focuses on illumination for working outdoors in the dark within the German railway network. Additionally, this special publication includes (i) limitations for using a headlamp as the sole light source and (ii) a checklist with 19 criteria to consider when buying a headlamp (DGUV 2021). We distributed the information in Austria as well as in Switzerland.

All workplace inspectors from the Social Accident Insurance for the Energy, Textile, Electrical and Media Products Sector (BG ETEM) received an instruction and additionally, two headlamps to present them and lend them to the companies working in the railway network.

Unfortunately, when we asked the manufacturer, it turned out that the modified headlamp is not a top seller. This could be attributed to various reasons. Firstly, the estimated number of required headlamps in the field of outdoor railway work in darkness is well below 1 000 units. Other reasons may include: (a) companies do not want to spend more money on better headlamps, (b) lack of awareness regarding the importance of good lighting – especially among buyers who are not specialized in health and safety issues, (c) buyers prefer high output to high timespan, (d) the selection of headlamps often takes place in bright environments or in darker environments without sufficient time for tests with dark adaptation (e) users do not pay attention to avoid dazzling others, (f) operators are so familiar with their work that they could do it even with closed eyes, (g) desire for one headlamp suitable for all lighting conditions including bright environment, etc. The latter issue could be solved by using a dimmable headlamp spanning a wide range of light settings.

4 Lighting requirements for headlamps

If the luminous flux is high, vision in the illuminated area improves, but at the same time the risk of glare increases. Therefore, there is no such thing as the optimal luminaire. Instead, a compromise must be found between the requirements for luminous flux, luminous intensity distribution, operating time and handling, whereas glare and disturbances of dark adaptation need to be avoided. Not to forget that the capacity of the battery decreases with an increasing light output.

4.1 Illuminance and beam angle

To measure illuminance (Table 3) for all different tasks a distance of 0,5 m was used. This equals more or less the distance between eye and visual task in the handle area. When walking in the track bed, a person's gaze is directed towards the ground at a distance of 1 m to 2 m in front of the person (corresponding viewing distance: 2 m to 3 m). Increase of the distance leads to a decrease of the illuminance. Therefore, it is beneficial to add an additional spot in the upper third of the light beam. This leads to a better uniformity of illuminance within the track bed (Figure 3 middle).

Table 3 – Requirements on illuminance, beam angle width and luminous intensity

Mode	Task	Viewing distance	Illuminance E_0*)	Beam angle width at $E_0/3$	Beam angle width at $E_0/10$	Luminous intensity I_0
1	Working within the handle area	0,5 m	50 lx	± 35°	± 37,5° to ± 50°	13 cd
2	Walking on railway tracks and orientation in the track bed	2 to 3 m	150 lx		≥ ± 27,5°	40 cd
3	Fixation of grounding rods	up to 10 m	1 000 lx		≈ ± 7,5°	250

*) measured in the centre of the light beam at a distance of 0,5 m towards to the luminaire

4.2 Spatial distribution

Illuminance should decrease from the middle towards the edge. For good vision in the surrounding environment as well, a low gradient effect, as shown in Figure 8, is strongly recommended. A low gradient effect enhances visibility of details in the dark surroundings. At construction sites for railway tracks and catenary it is especially relevant to be able to perceive dangers even in dark surroundings, to guarantee safety. With the highest illuminance E_0 in the middle, illuminance should measure $E_0/3$ in an angle of ± 35° and $E_0/10$ in an angle of ± 50°.

When working on railway tracks, vision of the surrounding environment can be lifesaving. It is relevant to perceive hazards as soon as possible.

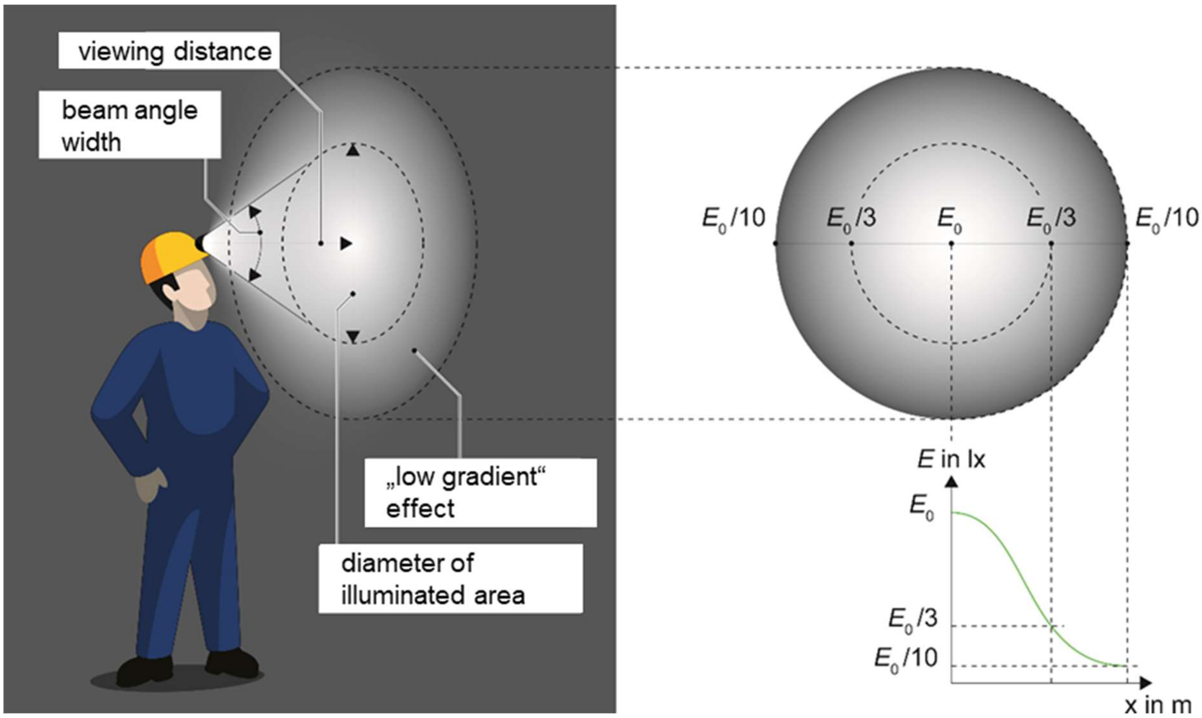

Figure 8 – Decreasing illuminance from the middle to the edge with a ”low gradient” effect to allow vision in the surrounding environment.

4.3 Glare

To avoid glare:

- the light emitting area of the luminaire should be as large as possible,
- its luminance should be well below 100 000 $cd \cdot m^{-2}$ and
- the LED chip (LED light source) should not be directly visible.

These goals can be achieved with optical components fixed on top of the LED chip. This is beneficial for the reduction of direct glare as well as reflected glare from glossy surfaces.

4.4 Flicker-free

Headlamps should be free of flicker, especially with low light levels. This can easily be achieved by dimming with constant current.

4.5 Ergonomic requirements

When mounting headlamps on a helmet, flexibility in adjusting the beam angle is essential. The lamp can be fixed e. g., by a click system or a ribbon, also depending on the position of the battery package. It can be positioned right next to the headlamp, at the back side of the helmet or it can be stored in the clothing. Latter solution offers advantages in terms of thermal management in hot or cold environments. The additional weight on the head should be well below 200 g to avoid stress on the upper cervical spine.

In the field study, an automatic reset to a lower light level was tested after using the boost mode, which involved a viewing distance of up to 10 m. Although, the time span was defined together with railway experts, it was not accepted by the subjects. Therefore, the duration of the battery runtime could not be guaranteed. Subsequently, it was agreed upon to use a signal to inform about the need for a battery charge. Due to occupational safety, green and red colour is prohibited in the railway environment.

4.6 Future prospects

We would like to discuss our findings and suggest additional standardization on top of the existing ANSI standard (ANSI 2019). This should be beneficial for the use of headlamps in brighter environments and for pocket lamps, too.

While we are convinced that most of our findings are ready to be implemented into standards, we would recommend to further investigate into necessary levels of illuminance for working in the dark. Perhaps we underestimated the impact of light pollution, the presence of additional lighting fixtures at the construction sites and the accustomed levels of illuminance, people are used to. Like other ergonomic optimizations, we strongly recommend to (a) instruct the users on how the headlamp works and the benefits of low illuminance levels, particularly when working with glossy objects. (b) Changes often need time for implementation, especially in the case of headlamps where people are accustomed to brighter light sources due to the lack of strongly dimmed options available in the market nowadays.

5 Conclusions

Higher luminous flux enhances vision in the illuminated area, but it also increases the risk of glare. As a result, there is no such thing as the perfect luminaire. Instead, a compromise must be found, considering requirements for luminous flux, luminous intensity distribution, operating time and handling, while minimizing glare and disturbances to dark adaptation. Ideally, this compromise should be tailored to the specific work tasks.

In addition to the ANSI Standard (2019), we recommend prescribing:

- that headlamps are dimmable or have several different light modes to adjust light output and luminous intensity distribution according to different tasks,
- that vision across the entire visual field is made possible,
- that there is absence of flicker at any light level and,
- that there is a reduced risk of direct and reflected glare.

As a minimum, we hope for the dissemination of the finding that utilizing lower illuminance and luminance levels is essential when employing headlamps for working in the dark.

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