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Project: Glare Effect for Visually Impaired Persons in Interior Displays of Public Transport Vehicles

Report

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Table of contents

Abstract

In this study, the following questions were investigated:
What are the threshold values with regard to psychological glare from lighting systems inside the vehicle when looking at displays for passenger information? Are there differences in these limits for persons with normal vision and persons with visual impairments?

First, concepts and approaches were determined that allow the UGR value known from architecture, which is used for glare assessment in lighting design in interiors with ceiling lighting for horizontal viewing direction, to be extended for arbitrary viewing directions and glare sources with arbitrary localization in the field of vision. A logical result of this extension is that the existing limits for UGR values, as they apply in architecture, have to be raised, since more light sources in the field of view are taken into account.
In the methodology for glare evaluation, on the one hand, the supplement to Iwata's UGR calculation was used; on the other hand, the UGR calculation is not carried out according to the common table method, but by means of mathematical-physical analysis of suitable digital images.
Furthermore, an experimental study was conducted with 20 normally sighted persons (visual acuity 0.8) and 17 persons with visual impairments and visual acuity ranging from 0.1 to 0.5.
The result of this study indicates that there is a massive difference in subjective glare perception between normally sighted persons and persons with visual impairments. An average UGR threshold value of 27 and 12 was measured for normal-sighted persons and persons with visual impairments, respectively. The UGR values of persons with visual impairments are so low that a practical uncompromising implementation seems impossible. Considering the fact that the majority of visually impaired people have an increased need for light, lowering the UGR to the aforementioned value of 12 would have a negative effect on this very part of the visually impaired population. Theoretical calculations based on our measurements of recent implementations suggest that the required reduction is not practical.
For persons with visual impairment, the use of other individual methods of protection against glare, e.g. sunglasses or visor caps, is considered reasonable, which is mostly already implemented.
According to the results of this study and according to our analysis of the practicability of lighting implementations, we propose a maximum value of UGR 22 with the recommendation to strive for a further reduction of 3 to 6 UGR values; in addition, we make some concrete suggestions on how these goals could be achieved.

A specific tool consisting of cost-effective commercially available components of digital photography as well as an open source program development (Windows based) completed the conceptual studies for the extension of the UGR calculation.

Zusammenfassung

In dieser Arbeit wurde folgenden Fragen nachgegangen:
Welche Grenzwerte gelten hinsichtlich psychologischer Blendung von Beleuchtungsanlagen im Fahrzeuginnern beim Blick auf Anzeigen zur Fahrgastinformation? Gibt es Unterschiede bei diesen Grenzwerten für normalsichtige Personen und Personen mit Seheinschränkungen?

Zuerst wurden Konzepte und Ansätze ermittelt, die es gestatten, den aus der Architektur bekannten UGR-Wert, der für das lichttechnische Design in Innenräumen mit Deckenbeleuchtung für horizontale Blickrichtung zur Blendungsbewertung dient, zu erweitern für beliebige Blickrichtungen und Blendlichtquellen mit beliebiger Lokalisierung im Gesichtsfeld. Ein logisches Resultat dieser Erweiterung ist, dass die bestehenden Grenzwerte für UGR-Werte, wie sie in der Architektur gelten, angehoben werden müssen, da mehr Lichtquellen im Gesichtsfeld berücksichtigt werden.

Bei der Methodik zur Blendungsbewertung wurde einerseits auf die Ergänzung der UGR-Berechnung von Iwata zurückgegriffen; andererseits wird die UGR-Berechnung nicht nach der gängigen Tabellenmethode, sondern mittels mathematisch-physikalischer Analyse geeigneter Digitalbilder vorgenommen.

Weiter wurde eine experimentelle Studie mit 20 normalsichtigen Personen (Visus $\geq$ 0.8) und 17 Personen mit Seheinschränkungen und Visus im Bereich von 0.1 bis 0.5 durchgeführt.

Das Resultat dieser Studie besagt, dass ein massiver Unterschied in subjektiver Blendempfindung zwischen Normalsichtigen und Personen mit Seheinschränkungen besteht. Ein durchschnittlicher UGR-Grenzwert von 27 bzw. 12 wurde für Normalsichtige bzw. Personen mit Seheinschränkungen gemessen. Die UGR-Werte der Personen mit Seheinschränkungen sind derart tief, dass eine praktische kompromisslose Umsetzung unmöglich erscheint. In Anbetracht der Tatsache, dass die Mehrzahl der Personen mit Sehbehinderung einen erhöhten Lichtbedarf haben, würde die Herabsetzung des UGR auf den vorerwähnten Wert von 12 eine negative Wirkung auf ebendiesen Teil der sehbehinderten Population nach sich ziehen. Theoretische Berechnungen auf der Grundlage unserer Messungen an neueren Implementationen lassen den Schluss zu, dass die geforderte Reduktion nicht praktikabel ist.

Für Personen mit Seheinschränkung wird die Verwendung anderer individueller Methoden zum Schutz vor Blendung z.B. Sonnenbrillen oder Schirmmützen als sinnvoll erachtet, was meistens schon umgesetzt wird.

Nach den Ergebnissen dieser Arbeit und gemäss unserer Analyse der Praktikabilität von Beleuchtungsimplementierungen schlagen wir einen Maximalwert von UGR 22 vor mit der Empfehlung eine weitere Reduktion um 3 bis 6 UGR-Werte zu anzustreben; dazu machen wir einige konkrete Vorschläge, wie diese Ziele erreicht werden könnten.

Die konzeptionellen Arbeiten zur Erweiterung der UGR-Berechnung wurde durch ein konkretes Tool aus kosteneffektiven handelsüblichen Komponenten der Digitalfotografie sowie eine open source Programmentwicklung (Windows basiert) abgerundet.

1. Introduction

1.1. Aim of the study

The aim of the study was to clarify the role of glare in interior displays of public transport. In particular, the study was intended to achieve:

1. An evaluation of the suitability of the metric to measure glare (UGR – Unified Glare Rating) adopted in the current norm to the assessment of glare in public transport
2. An assessment of the maximal glare that allows low-vision travelers to comfortably access the information on screens on public transport
3. The evaluation and subsequent development of a cost-effective, rapid and practicable solution to assess glare in public transport, usable without technical or specific know-how

1.2. Background

Travel information is of great importance in public transport and must be received in a timely and in a unambiguous manner by any traveler, independently from the travelers' impairments. A large amount of travel information is continuously available through screens. This poses the question on how to prevent that the difference in visual acuity between travelers significantly affect access to this information. Although normative work on this topic already exists, evaluation of the actual glare in the vehicles is only indirect as the regulations are based on estimates in a very different setting (i.e. building interiors/offices). Accordingly, a quantification of the glare threshold that allows travelers with reduced visual capacity to comfortably access screen information in the conditions encountered in a transport vehicle is needed. In the following sections we will provide: a definition of glare (section 1.2.1), a definition of "low vision" (section 1.2.2), an overview on the current norms regulating glare and their origin, highlighting the critical aspects with respect to the use in public transport (section 1.2.3), and an explanation of the current metric used to assess glare (section 1.2.4).

1.2.1. Glare

Glare is caused by the presence of areas in the vision field whose luminance exceeds the physiological perceiving limits of the visual system, which can be light sources or reflections of them. As consequences, there is visual discomfort as well as temporary loss of visual acuity (disability glare) (1). The DIN EN 12665 norms define discomfort glare as visual discomfort without reduction in visual function, caused by the presence in visual field of elevated luminance (2).

1.2.2. Low Vision

The World Health Organization (WHO) classifies vision impairment for distance in the following groups (3):

Mild	visual acuity between 0.3 and 0.5
Moderate	visual acuity between 0.1 and 0.3
Severe	visual acuity between 0.05 and 0.1
Blindness	visual acuity worse than 0.05

The experience with vision impairment is however subjective, and there are many factors, which affect this experience, like treatment intervention and vision rehabilitation (3).

Geographic and socioeconomic factors play a huge role in the prevalence of visual impairment worldwide: is estimated that in low-income areas there is a four times higher prevalence than in high-income regions.

The leading causes of visual impairment are uncorrected refractive errors, cataract, age-related macular degeneration, glaucoma, diabetic retinopathy, corneal opacity, and trachoma (3).

In Switzerland, more than 4 % (roughly 377000) of the population has a visual impairment, according to a publication of the Swiss National Association of and for the Blind (SNABlind). Of this group, almost 50000 are blind (4).

Visual impairment causes many burdens for the affected person. Children with visual impairment could experience delay in development and lower level of education (3). Accordingly, quality of life for adults with visual impairment is mostly reduced and higher rates of depression, lower rates of productivity, social isolation, difficulty accomplishing daily tasks, higher risk of falls and fractures are documented (3).

1.2.3. Norms regarding glare standard

There are several norms that attempt to ensure a minimum standard in the presentation of visual information. The trilogy of norms SN EN 16584: 2017 are binding both for cross-border rail and road traffic and, in particular, for so-called non-interoperable traffic. They regulate the art of presentation as well as e.g. the size of the characters and the contrast.

One of the aspects that must be considered is the amount of glare caused by illumination, which has to be limited to reduce the impact on reading comfort and to prevent hindering access to information on the screens. Glare depends on multiple factors concerning the intensity of the light but also e.g. the position of the luminaires and the overall background illumination of the observed area. This can be intuitively understood comparing the subjective sensation of glaring when a very strong light source is close to the object of our interest, or far away from it. Similarly, the same source of glare (e.g. a torch pointed to our eyes) will be perceived differently in darkness or in full sunlight.

The SN EN 16584-3 2017 defines the regulation for the minimum lighting for safe and comfortable use of vehicle of public transport, inclusive the access to visually presented information on screen. It states that information shall be easily readable in all lighting conditions and that lighting should not produce glare or reflectance referring to the methodology defined by CIE. The relevant normative work is thus the "CIE-117-1995, Discomfort in Interior Lighting" (4). This standard originates from architecture and was developed for people with normal vision in connection with office workplaces. This document defines a measurement of glare, named Unified Glare Rating (UGR) that can be used to quantify glare based on the properties of the illumination system (e.g. luminance and position of luminaires, etc.), and set limits for UGR in practical situations. It is however unknown whether this standard can be applied to other contexts that have completely different visual requirements and lighting conditions than office workplaces (e.g. as public transport vehicles). In particular, it should be questioned if and how, in this specific setting, the threshold values need to be adjusted to allow access to screen information for visual impaired people.

Beside the normative references, the effect of glare on people with low vision was addressed in a previous study from Nico Hauck (5). The study attempts to address different questions on the illumination needs of low vision people, ranging from minimum illumination and contrast to glare. The conclusion is that the glare threshold for low vision individuals who participated in the study was 6 UGR levels lower than that observed for individuals with normal sight. That study suggests that an UGR level of 13 should be aimed at for places where low vision individuals stay for prolonged time. The focus of the analysis was once again on interior lighting of houses, offices, and shops and on overall comfort. This is a critical difference with respect to our current focus, i.e., an analysis of glare in public transport with a special focus on the timely access to travel information on the screens. Among the setting differences it is fundamental to consider the relation between the position of the glaring light and the direction of the gaze. Luminaires in an office are usually not aligned with computer screen, while luminaires in a public transport are often close to the screens (as both are usually in the ceiling). Similarly, the non-glaring light to which the eye adapt is very different. In the study from Hauck, the fixation area luminance was set to 10 cd/m^2, a values that is quite low for even just considering the screen of public transport vehicles.

1.2.4. UGR

The Unified Glare Rating (UGR) as defined in "CIE-117-1995, Discomfort in Interior Lighting" is an effective, standardized metric to quantify discomfort glare given information on the illumination in the environment.

It is defined by the following formula:

$$UGR = 8log\left(\frac{0.25\sum\frac{L_i^2\omega_i}{p_i^2}}{L_b}\right)$$

Where L_b is the background luminance (in cd/m^2)

L_i is the luminance of the luminous parts of the luminaire *i* in the direction of the observer's eye (in cd/m^2)

ω_i is the solid angle of the luminous part of the luminaire *i* calculated at the observer's eye (in solid rad)

p_i is the Guth position index for the luminaire *i* (6)

The UGR formula is thus a ratio between the luminance of the glaring luminaires and the background luminance, which provides a reference to which the eye is adapted. This means that it can account for the different glare induced e.g. by a torch in darkness or in full sunlight. The luminance of each glaring luminaire is however squared, while the background luminance is not. Furthermore, the luminance of each glaring luminaires is multiplied by the visual angle that it covers, thus accounting not for the luminaire size directly, but for how such size is represented in the angular coordinate of the visual field. Altogether it is possible to intuitively consider the UGR formula as the squared sum of the Luminance of each glaring source as it is seen by the observing person (and thus defined in angular coordinates of the visual field) normalized by the “non-glaring” background luminance to which the eye of the observing person is adapted.
Very important to consider is the position index, which accounts for a critical corrective factor corresponding to the intuitive concept that the same solid angle of glaring light does not glare us equally at all positions and that anatomical aspects (e.g. eye brows) influence how light get to our eyes.
However, UGR remains a measure of relationship between the glaring and non-glaring luminance in the visual field, and it is therefore objective. This also means that it does not measure the discomfort glare. Many authors addressed the problem of mapping UGR with the subjective sensation of glare. For example, Carlucci et al. reported the degree of discomfort glare sensations associated to UGR values, as shown in Table 1 (7).

Sensation	**UGR**
Intolerable	34
Just intolerable	31
Uncomfortable	28
Just uncomfortable	25
Unacceptable	22
Just acceptable	19
Perceptible	16
Just perceptible	13
Imperceptible	10

Table 1: Scale of UGR values with corresponding sensation, after Carlucci et al.

It is important to add that progressively increasing the UGR will reach a level capable of inducing disability glare (with loss of visual acuity). In the current study, we only focused on discomfort glare.

The practical uses of UGR are rarely based on calculations using this formula. Estimations rely usually on simplified methods based on tables, who requires knowledge of the geometrical information on the rooms (e.g. ceiling high, distance from walls) and the luminaires locations, but do not requires direct calculation of solid angles of the luminaire in the visual field. The tables also resolve the issue of determining the adaptation light, which is the fundamental reference of the UGR formula, but it might be challenging to estimates. The calculation is replaced by approximation derived by room geometry, which has been verified in the context of office workplaces. This reflects the above-mentioned origin of UGR as a method for assessing glare during architectonic design or evaluation of interiors (offices, rooms, shops).

2. Recommendations regarding the use of UGR for assessment of discomfort glare in public transport

According to aim 1, the current study analysed the potential issues in using UGR to assess discomfort glare in public transport. Considering the mathematical basis of the UGR and the evidence in support of its broader use, we support the choice of using UGR in assessing discomfort glare in public transport as already in the SN (8). The UGR formula defined by CIE is indeed not specific of interior design. It simply provides an estimate of glare as ratio of the squared luminance from the glaring light source to the reference luminance (adaptation light) and correct the ratio using physiologically meaningful factors (i.e. the position index).

Critical for the use of the formula in a specific setting is how its elements are calculated. Specifically, the definition of background luminance (adaptation luminance) and the position index needs to be adapted. It is suggested to calculate the background luminance as the weighted average of all lights contributing to adaptation.

As light sources in the visual field have different influence on adaptation depending on the position in the visual field, weighing is done with the position indices according Guth and Iwata (6), i.e. the weighing factor is the reciprocal of the square of the position index.

For the position index, the main problem is that the Guth position index only considers illuminations coming from the upper half of the visual field, i.e. the upper hemisphere with respect of the line of sight (there are no indices for any position below the line of sight). This reflects the original development of the formula to evaluate glare in interior design, but it is not adequate for public transport vehicles. When considering a person riding a public transport vehicle and looking at an information screen on the ceiling, the luminaires, which covers the whole ceiling of the vehicle, appears, due to the prospective projections, both above and below the line of sight. An alternative set of position index has been developed by Iwata (6) complementing the Guth indexes with the values for the visual field below the line of sight. We thus recommend modifying the UGR formula using the Guth/Iwata index.

These two corrections have been implemented in the cost-effective UGR test system developed as part of this study (See Section 4) and used for the study presented in paragraph 3.

3. Comparison of glare thresholds for low- and normal-vision individuals in simulated public transport settings

3.1. Aim

The aim of this study was to assess the difference, if any, in the discomfort glare between low-vision and normal-vision participants. The assessment is based on the adaptation of the UGR formula discussed above and incorporates all considerations on its measurements in public transport from section 2. To maximize control of external factors, the study was performed in laboratory setting reproducing the glare relevant features for the task of reading information on a screen in public transport vehicles (see Figure 1 and details in “Experimental Setup” section).

3.2. Methods

Study design and Ethical approval

This was a prospective cross-sectional study. It was approved by the ethic committee Nordwest- und Zentralschweiz (EKNZ) and complied with the principles of the Declaration of Helsinki.

Participants

Forty volunteers were recruited from the staff and patient pool of the Optometry Department, University of Applied Sciences in Olten, Switzerland, or through associations for low-vision people. They were invited either by email or by personal invitation in the clinic.

The volunteers were screened and divided in two equally large groups, one including participants with visual impairment (low vision group) and the other without it (control group). Inclusion criteria for the control group were no eye disorders (assessed following participant’s statement) and visual acuity, with or without correction, greater or equal to 0.8. Participants of the low-vision group were recruited if the best visual acuity was between 0.1 and 0.5 and one or more underlying eye diseases were present.

Visual acuity was assessed with Landolt rings at a distance of 2 m for the participants without eye disorder and 1 m for participants with an underlying eye disease.

All volunteers were given a subject information sheet explaining the nature of the research, before giving signed consent. All measurements were conducted binocularly with best correction.

L-Viss questionnaire

The L-Viss (Leiden Visual Sensitivity Scale) questionnaire was used to assess the subjective perception of light sensitivity. The questionnaire consists of nine questions with the aim of evaluate the light sensitivity of the participants. The result score is between 0 and 36: the higher the score, the more sensitive is the participant to light. The L-Viss questionnaire is reported in the appendix I.

Experiment setup

Participants were positioned at a distance of 1.0 m from a 65 inches screen. The screen showed a picture of an internal ceiling display board of the passenger information system from FLP (Ferrovia Lugano-Ponte Tresa) taken from a passenger seat (Figure 1, left). From the passenger perspective the linear lightings on the ceiling of the car are seen as running behind the display board. This condition was chosen as model of the relative positions of glaring luminaires and screen.

To recreate a reading task based on this model, the part of the screen corresponding to display board was replaced by a list of names of real railway stops. The list was randomly changed at every measurement to grant that the reading challenge does not decline. On the left side of the display board three combined LED stripes were positioned and oriented to match the linear lighting of the depicted car of the FLP (Figure 1, right). The LED stripes were controlled by a software through a power supply device (RND). The two lateral LED stripes were controlled together, the central one was controlled separately. Through this arrangement, three different illumination settings (in the following referred to as “glare type”) were achieved: (a) all three LED stripes had same luminance, (b) the combined luminance of the lateral LED stripes were the same as the one of the central LED stripe and the sum of the three luminances is the same as in the case (a), (c) the combined luminance of the lateral LED stripes were the same as the one of the central LED stripe and the sum of the square of the three luminances is the same as sum of the square of the three luminance in the case 1. In other words, in type 2 and 3, the two lateral stripes have each half luminance than the central one. In type 2 the overall luminance was the same as in the case 1, while in type 3 the UGR value of the whole is the same as in case 1.

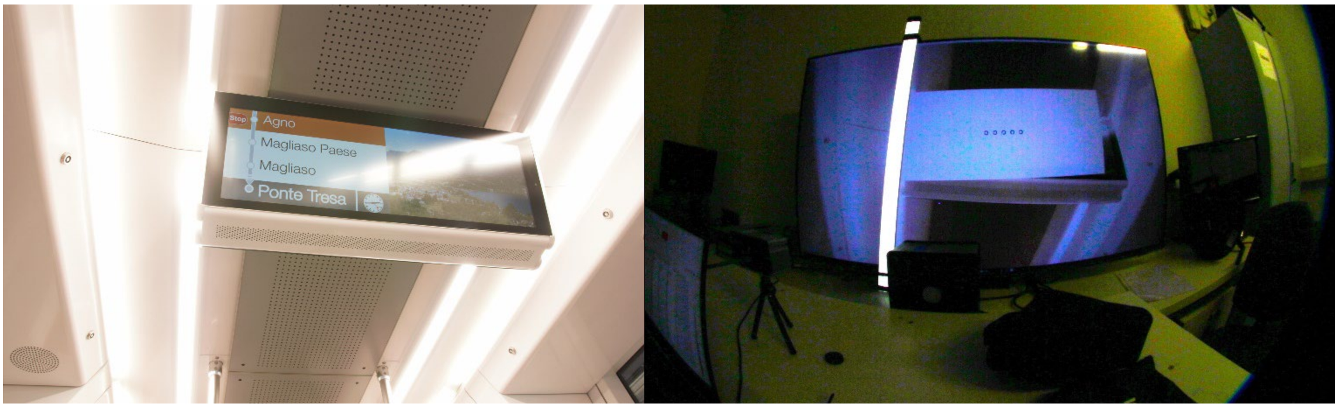


Figure 1: (left) picture taken on the FLP; (right) test situation, where the FLP picture is the background, the LED-stripes are positioned to cover the FLP illumination, and the visual acuity test is shown

A custom written software allowed the examiner to set the glare type and luminance of the LED stripes.

Experimental Procedures

Three measurements of glare sensitivity with different glare type, as described above, were carried out on each participant, with a break of 2 minutes between measurements. For each participant, the three types of glare setting were presented once, in random order.

Room light was switched off before the first measurement to eliminate any additional light source. During the breaks between tests of the different glare type, the room light was turned on, matching the illumination level present at the beginning of the experiment. This prevented any adaptation effect and reset the eye adaptation to light before testing each condition.

During each measurement, the luminance of the LED stripes was progressively increased, and the participants were asked to report glare using a numeric scale. The scale was based on that used by Ngai and Boyce,(9) adapting the description of reaction to match our task and condition. Table 2 report the grading scale. Each measurement was continued until the participants responded with a 6 on the grading scale. The first value of luminance, for which the subject's response was 5, was used to calculate the UGR discomfort threshold. This means that the "description" associated with 5 is what we considered the level of discomfort that it should not be exceeded.

Grade	Name	Description of reaction
1	Imperceptible	I am not aware of anything
2		I am aware there is something but cannot tell what it is
3	Noticeable	I am aware of the presence of a glare, but it does not bother me
4		I am aware of a glare, and I wish it was not there
5	Uncomfortable	I am aware of a glare, and it troubles me.
6		I am aware of a glare and if somebody doesn't do something about it I will take direct action myself
7	Intolerable	I am aware of a glare, and I will not stay here a moment longer

Table 2: Grading scale of glare

3.3. Results

Participants

Twenty participants without visual impairment (11 female) and 17 with visual impairment (9 female) completed the study. The mean age (± sd) was 40.6 ± 19 years (28.6 ± 9.0 years and 54.7 ± 19.2 years for participants without resp. with visual impairment). The reasons of low vision of participants with impaired vision were congenital or acquired, such as: retinitis pigmentosa, age-related macular degeneration, central retinal artery occlusion, aniridia, or Crouzon syndrome (list not exhaustive). The average (± sd) visual acuity in the group without visual impairment was 0.98 (± 0.17); in the group with visual impairment 0.13 (± 0.06).

Glare

No statistical significance in UGR was found among glare type or order of presentation of the glare type in neither of the two groups. A significant difference in UGR discomfort threshold, defined as 5 on the scale showed above (Table 2) between the two groups was found. ($p<0.001$). According to the results data from the different presentation type and presentation order were pooled and the UGR discomfort thresholds for the low vision and control group are presented in Figure 2. The mean UGR discomfort threshold in participants without visual impairment was 27.6 (± 5.9) while in the group with visual impairment, the mean UGR discomfort threshold was 12.4 (± 3.2). The upper and lower values of the 95% confidence interval were 24.7-30.4 for the participants without visual impairment and 10.6-14.15 in the group with visual impairment.

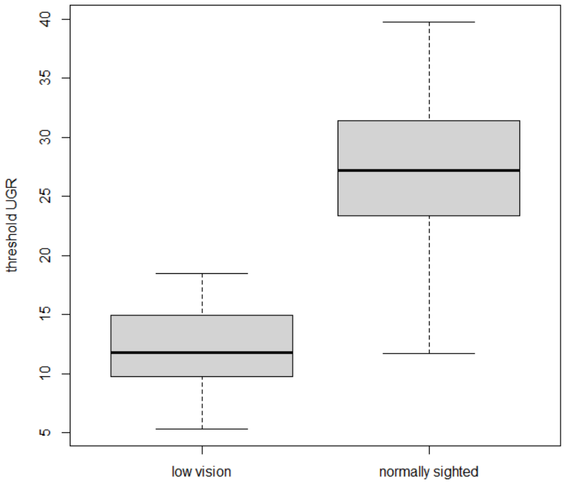


Figure 2: UGR-threshold by participant group

L-Viss questionnaire

A significant difference between the two group was found also for the L-Viss questionnaire. Mean score (± sd) was 10.2 ± 5.0 resp. 17.5 ± 5.3 for the group without resp. with visual impairment ($p < 0.001$).

3.4. Discussion

The results of the study demonstrate a massive difference between visually impaired and non-visually impaired participants in the UGR level that leads to discomfort in a reading task (in a simulated public transport setting). The visually impaired participants suffer from discomfort at UGR values at least 10 UGR levels lower than the non-visually impaired participants. Interestingly, the latter reach the discomfort threshold at an elevated UGR level, matching the thresholds previously suggested for task with low visual demand (UGR-value between 25 and 28) (5). On the other hand, the UGR values causing discomfort in visually impaired participants, even considering upper 95% value of the confidence interval, is 2 points lower than the one indicated for highly demanding tasks.

The observed difference (>10 UGR levels) is larger than the one reported by a previous study (6 UGR levels) (5). The same study suggested a UGR level of 13 as discomfort threshold for visually impaired individuals, which is above the average discomfort threshold of the tested visually impaired participants in our study. This evidence could possibly be explained by the combined effect of the position of LED, which mimics the illumination in a public transport vehicle, and task, which, mimicking the demand of a screen with travel information, requires visual focus to rapidly read the name of the stations.

To put the thresholds observed in the visually impaired participants in a more comprehensible perspective, Carlucci et al. states that an UGR of 13 is associated with a just perceptible glare for normal sighted people (as shown in the table 1) (7). This suggests, that adjusting vehicle and display luminance to the UGR level, for which the visually impaired participants are not uncomfortable, and at the same time maintaining the access to the information, would be practically impossible. Further consideration supporting these statements are details in the conclusion section.

An additional finding of the study is the absence of difference with respect to the way the luminance is distributed within the luminaires. It is often speculated that smoothing the luminance at the edge may decrease glare. This was not observed in any of the two groups tested, suggesting that it is the overall luminance leading to the glare, rather than its distribution within the luminaire, further confirming the goodness of the UGR formula.

3.5. Conclusion

In this study a working tool to calculate UGR values for any visual axis was developed. This tool included a cost-effective hardware and a software dedicated to the purpose of calculating UGR in an easy, unambiguous, and intuitive way. This tool, its working principle and use is described in detail in a separate document.

As part of the development of this working tool, the UGR formula was further developed. On one hand, the position index according to Guth was modified to include the lower visual field by using the method and formula of Iwata. On the other hand, the method of calculating UGR values with tables was generalized to digital methods using digital images.

In an experimental study with normally sighted and visual impaired participants it was found that the former easily tolerate UGR values up to 27, when asked to perform a reading task in an experimental setup simulating the glaring conditions of a ceiling information screen in a public transport vehicle. On the other hand, low vision participants showed to be clearly more sensitive to glare: already at a UGR value of 12, the majority of tested low vision participants rated the glare as uncomfortable.

To correctly understand the implications of this result, it is important to clarify that the measured UGR threshold refers to discomfort (discomfort glare) and there is no association with reduction of visual functions.

The result implies that to achieve an acceptable situation for visually impaired people, the UGR value of the lighting arrangement would have to be lowered by 15 units. However, a theoretical analysis based on data we collected during field tests (section 4.2 for details) and on the mathematics of UGR formula suggests that solutions that fully satisfy this very high demand with respect to glare are likely not practicable in public transport vehicle. The theoretical analysis can be summarized and explained as follow:

The situation in the vehicles we conducted field test in is the following:

- We have examined two implementations and measured their UGR values according to Guth / Iwata / FHNW with the methodology detailed in section 4. The observed UGR were around 26.5 (MGB, Orion) and 21.5 (Limmatthalbahn, AVA, FLP).

The assumptions of the theoretical analysis for lowering the UGR levels are as follows:

- A reduction of the UGR value of the lighting also leads to a reduction of glare sensation
- Adaptation luminance is linearly related to the luminance of the lighting arrangement.

Analyzing the UGR-formula, the following two conclusions can be made with respect to the effect of practicable intervention types to lower the UGR:

1. Intervention type: Reduction of the illuminance

According to the standard, 150 lx illumination or more are required. In the two trains, in which the UGR measurements were done, the illuminance was between 500 and 600 lx. Considering that elderly and the majority of visual impaired people have a need for light up to four times higher than normal sighted people (10), the two vehicles mentioned above meet this requirement. If the luminance would be reduced by a factor of 4.0, the risk of accidents and discomfort for a large proportion of rail users will be increased.
If the luminance would be lowered by a factor of $\alpha = 4.0$ despite of these facts, what improvement would be achieved thereby? An inspection of the UGR formula shows that the improvement in UGR may be calculated by:

$$\Delta UGR = 8 \cdot \log_{10} \alpha \approx 4.8$$

This lowering of UGR is far below what is needed to achieve the UGR threshold causing no discomfort for visually impaired people. Thus, a reduction of a factor of 4 will have the downside of increased risk of accidents and injuries and lower comfort, without achieving the desired UGR goal.

2. Intervention type: Reduction in luminance with a simultaneous increase in spatial extent (or solid angle) of the light sources

Another approach to reduce UGR values is to reduce the luminance of light sources **and** increase their spatial extent such that the total light flux remains the same. If the luminance is reduced by the factor α and the overall solid angle of the light sources is increased by the same factor α, the change in UGR value is again calculated according to the formula

$$\Delta UGR = 8 \cdot \log_{10} \alpha$$

An improvement of the UGR value by 10 units would mean an increase of the illumination extension by a factor of 17.8!
Taking the tested vehicles with the lower UGR values as an example (UGR=21.5 - Limmatthalbahn, AVA, FLP) and assuming that essentially only the ceiling area can be used for lighting, it becomes clear that such a factor is not feasible.

Further consideration and suggestions

The fact that a factor of α = 17.8 is not feasible does not mean that a step in this direction cannot be taken.

According to our findings and the practicability of the changes, we would consider the following two UGR values as proposal:

- Maximum acceptable value for UGR = 22
- Recommendation: 3 to 6 UGR units lower than the maximum acceptable (practicability-based tradeoff)

Recommendations for the continuation of this work:

- The very high glare sensitivities found in this experimental study in visually impaired participants from the German-speaking part of Switzerland should be tested with larger population for further validation and generalization of the finding.
- The planner/lighting designer should have a tool that allows UGR values to be calculated from an existing lighting arrangement. In this work, no such planning tool could be created for reasons of limited resources.

A limitation of this study and any study on discomfort glare is that there is no evidence-based knowledge on discomfort glare perception and the associated reduction in visual performance, neither for normal sighted nor visually impaired people.

Further remarks for planning and light designers

The required illuminance levels inside vehicles in the seating areas have not been changed from SN EN 13272:2001 to SN EN 13272-1:2020 and are still ≥ 150 lx. In reality, today the luminance levels in these areas have increased to values several times higher. It is important to note that the seating area accommodates older travelers and the majority of the visually impaired, approx. ⅔, who require more illumination for their visual performance.

In the light of this and the previous theoretical considerations, the following measures can thus be suggested:

- Reduction of illuminance levels (works for energy saving as well).
- Shielding the intrinsic luminance by setting it back from the surrounding surface.
- Reducing the intrinsic luminance of the luminaire by:
    - Increasing the number
    - Increasing the luminance areas with simultaneous reduction of the luminance levels
- Reduction of the luminance of the luminaires by:
    - specular louvre luminaires

- enclosures with Fresnel diffusing lens-stepped lens with
    - linear structure
    - point structure

Considering the challenge to reduce glare, the current individual interventions that reduce discomfort (such as using sunglasses, shielding caps, lowering direction of gaze, etc..) are further supported.

4. Cost-effective UGR-measuring system

The third aim of this project was to evaluate and subsequent develop a cost-effective, rapid and practicable solution to assess glare in public transport, usable without specific technical know-how.

4.1. Camera

Our evaluations and pilot tests as well as theoretical consideration evidenced that he following factors connected to the acquisition and processing of the images have a critical influence on the UGR calculation:

1. Inclusion of the largest possible visual field (via wide-angle objective)
2. Avoidance of saturation in any pixels, to correctly estimate luminance
3. Prevention of effect of light source frequency on the luminance capture in a single picture

After evaluating different hardware combinations, e.g. with variable or fixed filter, camera with different focal lengths, different f-number, to control the factors reported above, we selected a solution that optimizes the practicability, while allowing flexibility when needed.
The selected solution is a Sony Alpha 5000 with a fisheye objective Meike MK-EW55 6.0 mm - 11 mm. A variable neutral density filter (Vizelex Cine ND Throttle Lens Mount Adapter) with light reduction between 1 and 8 stops, was added to avoid pixel saturation without decreasing the shutter speed (which increases the risk associated with factor 3 listed above).

4.2. Field tests

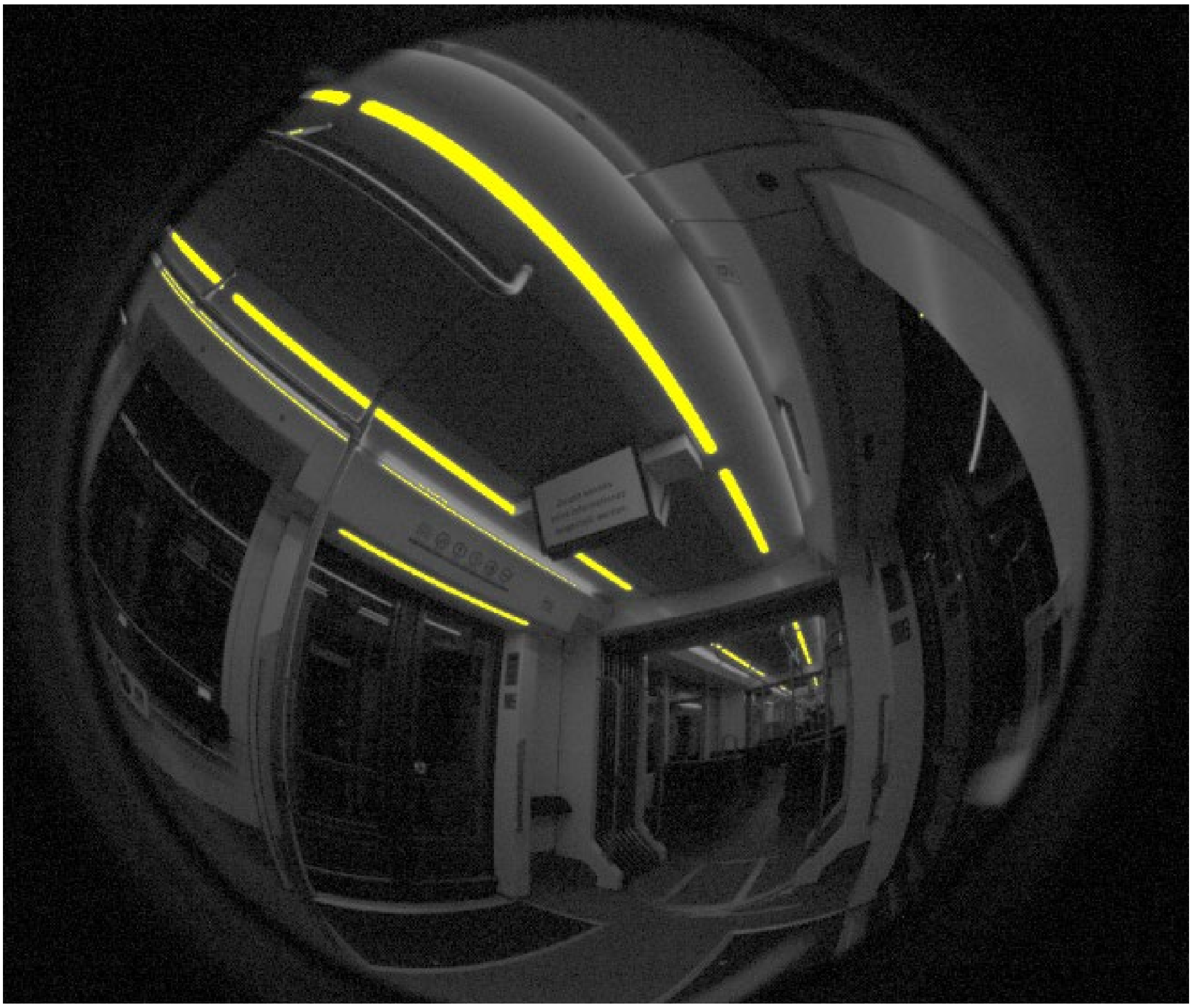
This system was tested in two different public transport vehicles. In both situations, the measurements were taken at the deposit, with the vehicle stationary and at night, to eliminate every light source outside the vehicle. The interior light setting of the vehicles was the one used for the daily operation.
After adjusting the setting of the camera, some seats estimated to be subject to greatest possible glare were chosen as location for the measure. The camera was positioned on a tripod on a height simulating the position of a person's eyes, looking at the display.
The results are shown in the following table:

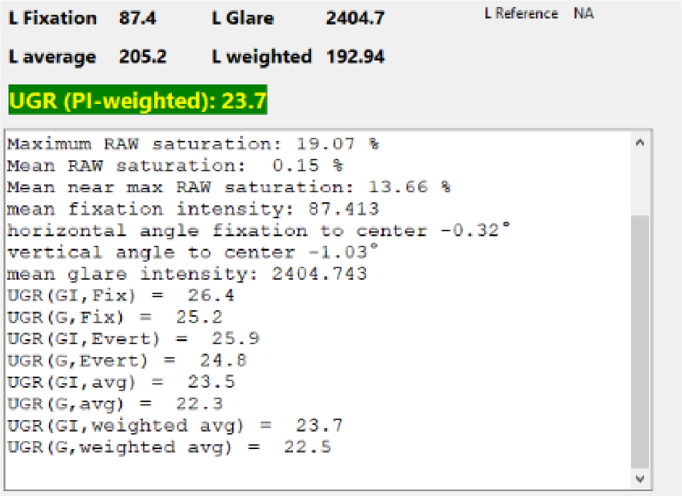
Vehicle	UGR range
Tram of Limmatalbahn	[21.9, 23.4]
Train of Matterhorn-Gotthard-Bahn	[26.3, 27.6]

Table 3: Results of UGR measurements in the two different vehicles

A couple of measurements, as example, are shown below.

- Limmatalbahn





L Fixation 87.4 **L Glare** 2404.7 L Reference NA

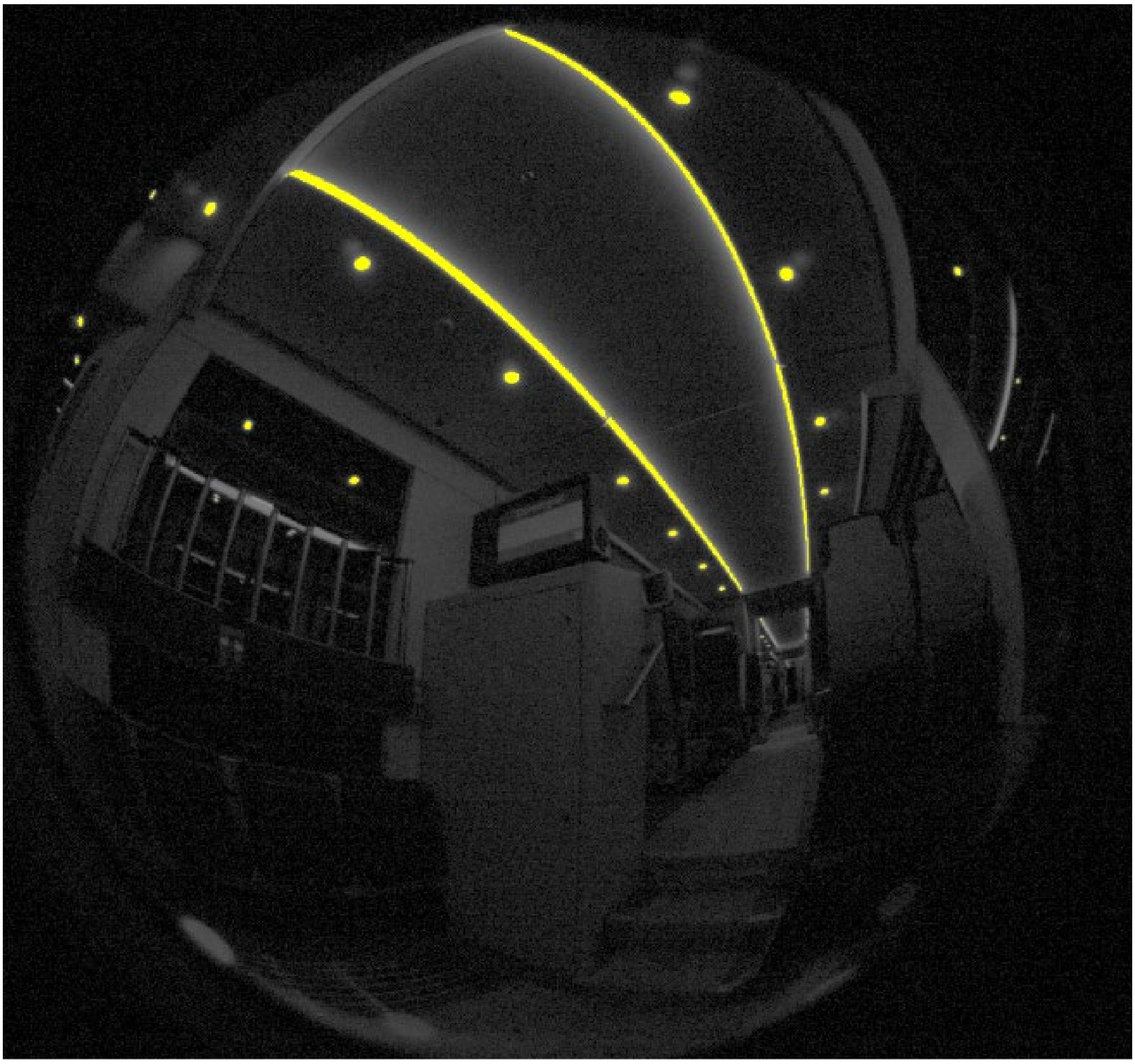
L average 205.2 **L weighted** 192.94

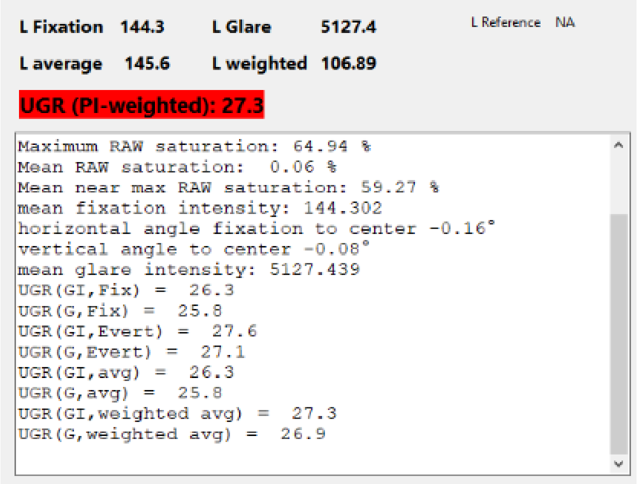
UGR (PI-weighted): 23.7

```
Maximum RAW saturation: 19.07 %
Mean RAW saturation:  0.15 %
Mean near max RAW saturation: 13.66 %
mean fixation intensity: 87.413
horizontal angle fixation to center -0.32°
vertical angle to center -1.03°
mean glare intensity: 2404.743
UGR(GI,Fix) =  26.4
UGR(G,Fix) =  25.2
UGR(GI,Evert) =  25.9
UGR(G,Evert) =  24.8
UGR(GI,avg) =  23.5
UGR(G,avg) =  22.3
UGR(GI,weighted avg) =  23.7
UGR(G,weighted avg) =  22.5
```

Figure 3: Measurement of UGR in a vehicle of the Limmatalbahn, looking at the display; on the left: UGR value

- Matterhorn-Gotthard-Bahn





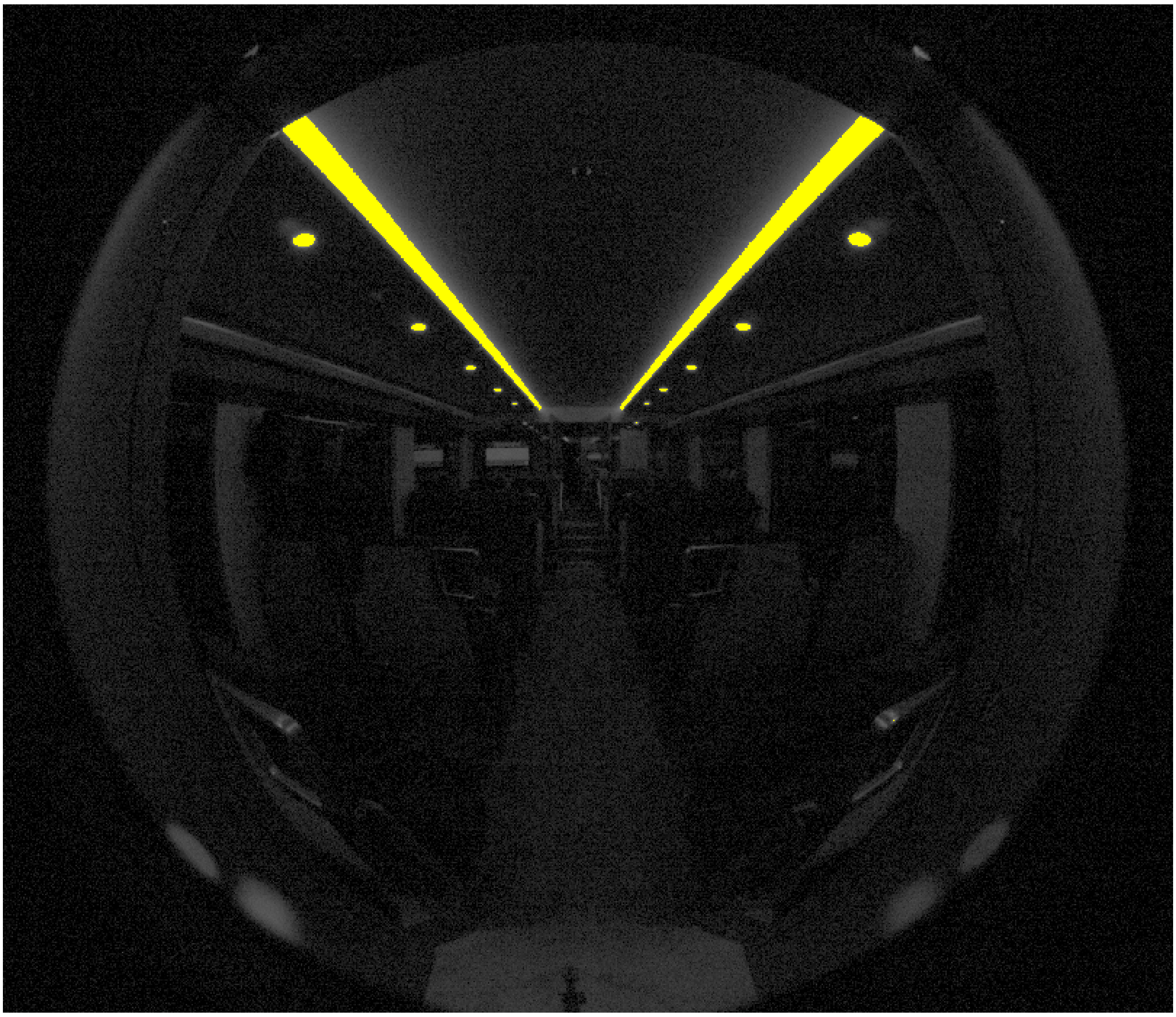
L Fixation 144.3 **L Glare** 5127.4 L Reference NA

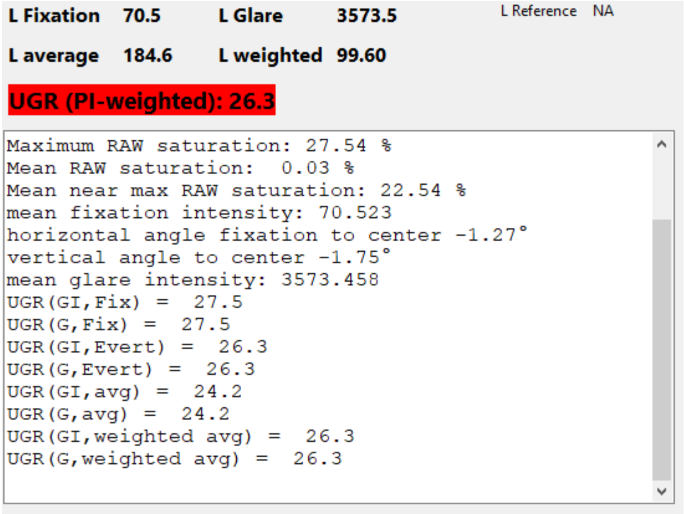
L average 145.6 **L weighted** 106.89

UGR (PI-weighted): 27.3

```
Maximum RAW saturation: 64.94 %
Mean RAW saturation:  0.06 %
Mean near max RAW saturation: 59.27 %
mean fixation intensity: 144.302
horizontal angle fixation to center -0.16°
vertical angle to center -0.08°
mean glare intensity: 5127.439
UGR(GI,Fix) =  26.3
UGR(G,Fix) =  25.8
UGR(GI,Evert) =  27.6
UGR(G,Evert) =  27.1
UGR(GI,avg) =  26.3
UGR(G,avg) =  25.8
UGR(GI,weighted avg) =  27.3
UGR(G,weighted avg) =  26.9
```

Figure 4: Measurement of UGR in a vehicle of the Matterhorn-Gotthard-Bahn, looking at the display from a seat; on the left: UGR value





L Fixation 70.5 **L Glare** 3573.5 L Reference NA

L average 184.6 **L weighted** 99.60

UGR (PI-weighted): 26.3

```
Maximum RAW saturation: 27.54 %
Mean RAW saturation:  0.03 %
Mean near max RAW saturation: 22.54 %
mean fixation intensity: 70.523
horizontal angle fixation to center -1.27°
vertical angle to center -1.75°
mean glare intensity: 3573.458
UGR(GI,Fix) =  27.5
UGR(G,Fix) =  27.5
UGR(GI,Evert) =  26.3
UGR(G,Evert) =  26.3
UGR(GI,avg) =  24.2
UGR(G,avg) =  24.2
UGR(GI,weighted avg) =  26.3
UGR(G,weighted avg) =  26.3
```

Figure 5:Measurement of UGR in a vehicle of the Matterhorn-Gotthard-Bahn, standing in the middle of the aisle looking straight ahead; on the left: calculated UGR value

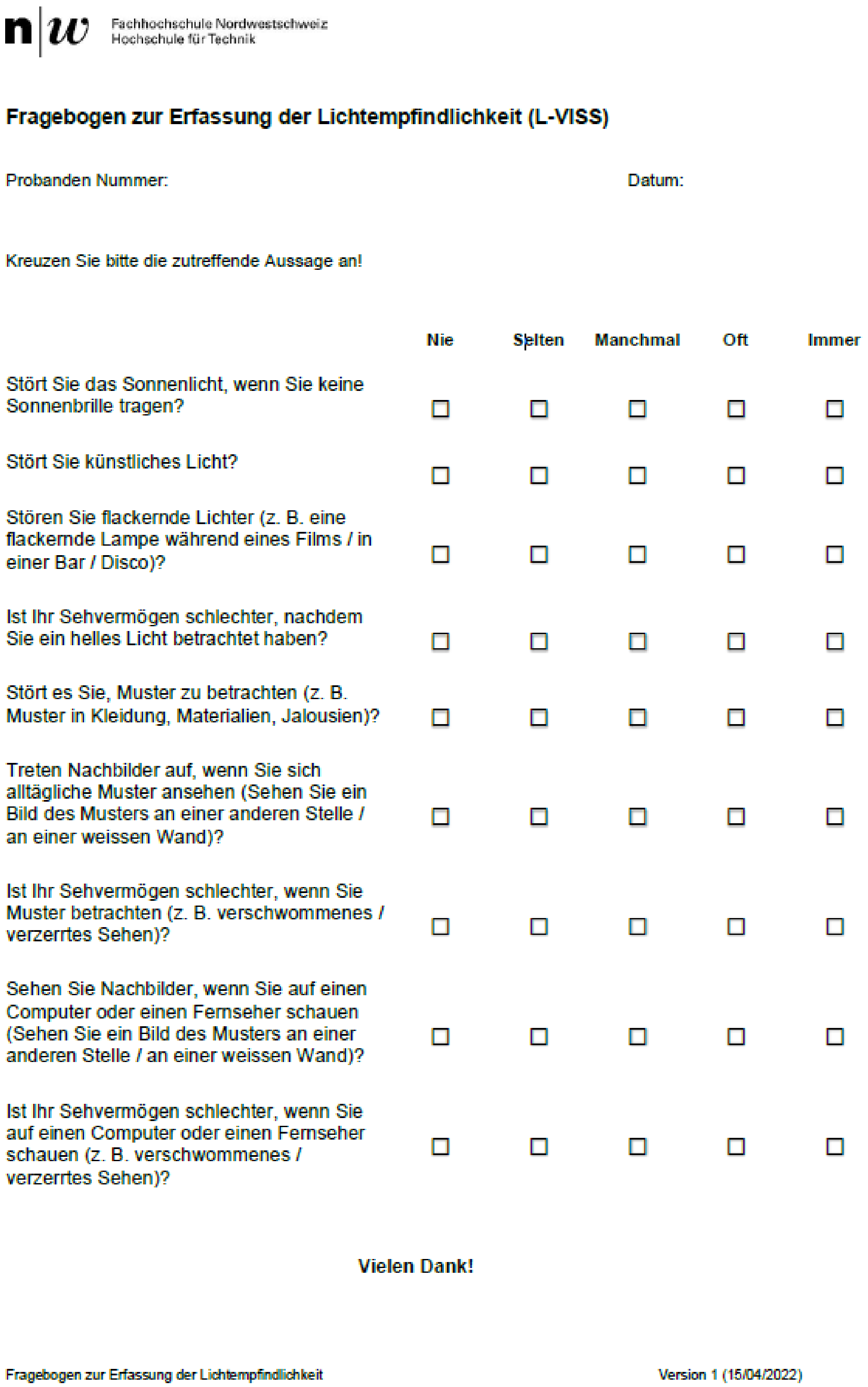
5. Literature

1. Chiabrando R, Fabrizio E, Garnero G. The territorial and landscape impacts of photovoltaic systems: Definition of impacts and assessment of the glare risk. Renew Sustain Energy Rev. 1. Dezember 2009;13(9):2441–51.
2. DIN EN 12665:2018-08, Licht und Beleuchtung_- Grundlegende Begriffe und Kriterien für die Festlegung von Anforderungen an die Beleuchtung; Deutsche Fassung EN_12665:2018 [Internet]. Beuth Verlag GmbH; [zitiert 8. November 2022]. Verfügbar unter: https://www.beuth.de/de/-/-/279496365
3. Vision impairment and blindness [Internet]. [zitiert 8. November 2022]. Verfügbar unter: https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment
4. Sehbehinderung: Entwicklung in der Schweiz [Internet]. Tactuel. 2020 [zitiert 8. November 2022]. Verfügbar unter: https://www.tactuel.ch/sehbehinderung-entwicklung-in-der-schweiz/
5. Hauck N. Erarbeitung visuell barrierefreier Licht- und Beleuchtungslösungen zur Steigerung der Orientierung und Mobilität sehbehinderter Menschen in Gebäuden. [Wien]: Technische Universität Wien; 2017.
6. Iwata T, Tokura M. Position Index for a glare source located below the line of vision. Int J Light Res Technol. 1. September 1997;29(3):172–8.
7. Carlucci S, Causone F, De Rosa F, Pagliano L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renew Sustain Energy Rev. 1. Juli 2015;47:1016–33.
8. SN EN 13272:2001 Bahnanwendungen - Elektrische Beleuchtung in Schienenfahrzeugen des öffentlichen Verkehrs.
9. Ngai P, Boyce P. The Effect of Overhead Glare on Visual Discomfort. J Illum Eng Soc. 1. Juli 2000;29(2):29–38.
10. Schierz C. UGR-Verfahren – Anwendung und Grenzen. ZVEI: Die Elektroindustrie; 2021.

6. Table of Figures

7. Table of Tables

1 Appendix I: L-Viss questionnaire



Fachhochschule Nordwestschweiz
Hochschule für Technik

Fragebogen zur Erfassung der Lichtempfindlichkeit (L-VISS)

Probanden Nummer: Datum:

Kreuzen Sie bitte die zutreffende Aussage an!

	Nie	**Selten**	**Manchmal**	**Oft**	**Immer**
Stört Sie das Sonnenlicht, wenn Sie keine Sonnenbrille tragen?	☐	☐	☐	☐	☐
Stört Sie künstliches Licht?	☐	☐	☐	☐	☐
Stören Sie flackernde Lichter (z. B. eine flackernde Lampe während eines Films / in einer Bar / Disco)?	☐	☐	☐	☐	☐
Ist Ihr Sehvermögen schlechter, nachdem Sie ein helles Licht betrachtet haben?	☐	☐	☐	☐	☐
Stört es Sie, Muster zu betrachten (z. B. Muster in Kleidung, Materialien, Jalousien)?	☐	☐	☐	☐	☐
Treten Nachbilder auf, wenn Sie sich alltägliche Muster ansehen (Sehen Sie ein Bild des Musters an einer anderen Stelle / an einer weissen Wand)?	☐	☐	☐	☐	☐
Ist Ihr Sehvermögen schlechter, wenn Sie Muster betrachten (z. B. verschwommenes / verzerrtes Sehen)?	☐	☐	☐	☐	☐
Sehen Sie Nachbilder, wenn Sie auf einen Computer oder einen Fernseher schauen (Sehen Sie ein Bild des Musters an einer anderen Stelle / an einer weissen Wand)?	☐	☐	☐	☐	☐
Ist Ihr Sehvermögen schlechter, wenn Sie auf einen Computer oder einen Fernseher schauen (z. B. verschwommenes / verzerrtes Sehen)?	☐	☐	☐	☐	☐

Vielen Dank!

Fragebogen zur Erfassung der Lichtempfindlichkeit Version 1 (15/04/2022)