Supplementary material

of the article *"Cross-validation and robustness of daylight glare metrics"*

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Nomenclature

E	Illuminance [lux]
E_{dir}	Direct Illuminance (illuminance only by the glare sources) [lux]
E_{ind}	Indirect Illuminance (illuminance only by the background) [lux]
E_v	Vertical Illuminance [lux]
L	Luminance [cd/m^2]
L_s	Mean Luminance of the glare source [cd/m^2]
L_t	Mean Luminance of the task [cd/m^2]
L_b	Background luminance [cd/m^2]
ω	Solid angle
ω_s	Solid angle subtended by the glare source [sr]
Ω_s	Solid angle subtended by the glare source modified by the position of the source with respect to field of view and Guth's position index [sr]
P	Position index [-]

Subscripts

adapt	Adaptation
avg	Average
b	Background
c	Ceiling
dir	Direct
f	Floor
i	Summation index
ind	Indirect
n	Number of glare sources
s	Glare source
t	Task
v	Vertical
w, win	Window

2. Selection of glare metrics – equations and definitions

In the following sections, the equations and/or definitions of the selected glare metrics are shown.

2.1 CIE Glare Index CGI [5,6]

$$CGI = 8 \cdot \log 2 \cdot \frac{\left[1 + \frac{E_{dir}}{500}\right]}{E_{dir} + E_{ind}} \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}$$

2.2 Daylight Glare Index DGI [7,8]

$$DGI = 10 \log 0.478 \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \cdot \Omega_{s,i}^{0.8}}{L_b + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{s,i}}$$

2.3 Modified Daylight Glare Index DGI_{mod} [9]

$$DGI_{mod} = 10 \log 0.478 \sum_{i=1}^{n} \frac{L_{s,i}^{1.6} \cdot \Omega_{s,i}^{0.8}}{L_{avg}^{0.85} + 0.07 \cdot \omega_{s,i}^{0.5} \cdot L_{s,i}}$$

With

$$L_{avg} = \frac{E_v}{\pi}$$

Note: In the original publication the equation is printed without the sum sign. In this study we used above equation, which uses the sum of all glare sources, in case there are multiple detected.

2.4 Daylight Glare Probability DGP [10,11]

$$DGP = 5.87 \cdot 10^{-5} \cdot E_v + 9.18 \cdot 10^{-2} \cdot \log(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}) + 0.16$$

2.5 Direct Illuminance E_{dir} [12]

E_{dir} is the illuminance induced only by glare source(s).

2.6 Vertical Illuminance E_v [10,14]

E_v is the illuminance in a vertical plane at eye level.

2.7 Glare Sensation Vote GSV [17]

$$GSV = 1.61 + 0.152 \cdot L_{s\%2000C} + 0.019 \cdot \frac{L_s}{L_t}$$

With

$L_{s\%2000C}$ is the solid angle ratio of pixels larger or equal 2000 cd/m^2 within central and near FOV.

2.8 Average Luminance in 40° Band L_{40band_avg} [3]

L_{40band_avg} is the average luminance in a horizontal 40° band around the middle axis of an HDR image.

2.9 Average Luminance in Image L_{avg} [2]

L_{avg} is the average luminance of the 180° HDR image, using the mathematical definition:

$$L_{avg} = \frac{1}{2\pi} \sum_{i=1}^{all\_pixels} L_i \cdot \omega_i$$

2.10 Average Luminance of Window L_{avg_win} [3,10]

L_{avg_win} is the average luminance of the window area, using the mathematical definition.

$$L_{avg\_win} = \frac{\sum_{i=1}^{all\_window\_pixels} L_i \cdot \omega_i}{\sum_{i=1}^{all\_window\_pixels} \omega_i}$$

2.11 Median Luminance of Image L_{med} [3]

L_{med} is the median luminance within the 180° HDR image.

2.12 Median Luminance of Lower Window (< 2 m height) $L_{med\_lowerwin}$ [3]

$L_{med\_lowerwin}$ is the median luminance of the lower part of a window, with a maximum height of 2 m.

2.13 Median Luminance of Window L_{med_win} [3]

L_{med_win} is the median luminance of the window area.

2.14 Position Index Weighted Average Luminance of Image L_{pos_avg}*

L_{pos_avg} is the average luminance of the 180° HDR image, where each pixel is divided by the corresponding position index value P.

*personal communication between Jan Wienold and Werner Osterhaus

2.15 Standard Deviation of the Luminance of the Window L_{std_win} [3]

L_{std_win} is the standard deviation of the luminance in the window area.

2.16 Perceived Glare Level for typing task PGL [13]

$$PGL = 0.206 + 0.00016 \cdot L_s + 0.00337 \cdot R_t$$

With

$$R_t = \frac{L_s}{L_t}$$

2.17 Predicted Glare Sensation Vote PGSV [16]

$$PGSV = PGSV_{con} \quad \text{if} \quad \frac{L_s}{L_b} > \frac{L_{avg}}{L_{adapt}} \quad \text{(contrast glare)}$$

$$PGSV = PGSV_{sat} \quad \text{if} \quad \frac{L_s}{L_b} \leq \frac{L_{avg}}{L_{adapt}} \quad \text{(saturation glare)}$$

With

$$L_{adapt} = L_t$$

$$PGSV_{con} = 3.2 \cdot \log L_{win} + (0.79 \cdot \log \omega_{win} - 0.61) \cdot \log L_b - 0.64 \cdot \log \omega_{win} - 8.2$$

$PGSV_{sat}$ see 2.18

L_{win} : Average luminance of window (calculated according to 0)
ω_{win} : Solid angle of window

Note: In the original publication the approximation of the average luminance is used:

$$L_{avg} = \frac{E_v}{\pi}.$$

In this study we used the mathematical definition of the average luminance instead (see 2.9).

Following this, we used for the calculation of the background luminance L_b the mathematical definition:

$$L_b = \frac{2\pi \cdot L_{avg} - \omega_{win} \cdot L_{win}}{2\pi - \omega_{win}}$$

2.18 Predicted Glare Sensation Vote (saturation glare) PGSV$_{sat}$ [15]

$$PGSV_{sat} = \frac{-0.57 - 3.3}{1 + \left({L_{avg}}/{1250} \right)^{1.7}} + 3.3$$

The average luminance is used as:

$$L_{avg} = \frac{E_v}{\pi}.$$

In this study we used the mathematical definition of the average luminance instead (see 2.9).

2.19 Unified Glare Probability UGP [4]

$$UGP = 0.26 \cdot log \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}$$

2.20 Unified Glare Rating UGR [6]

$$UGR = 8 \cdot log \frac{0.25}{L_b} \sum_{i=1}^{n} \frac{L_{s,i}^2 \cdot \omega_{s,i}}{P_i^2}$$

2.21 Experimental Unified Glare Rating UGR$_{exp}$ [9]

$$UGR_{exp} = 8 \cdot \log L_{avg} + 8 \cdot log \sum_{i=1}^{n} \frac{L_{s,i} \cdot \omega_{s,i}}{L_b \cdot P_i^2}$$

with

$$L_{avg} = \frac{E_v}{\pi}$$

2.22 Visual Comfort Probability VCP [18]

$$VCP = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374-1.3227 \ln DGR} e^{-t^2/2} dt$$

With

$$DGR = \left(\sum_{i=1}^{n} M_i \right)^{n^{-0.0914}}$$

$$M_i = \left(\frac{0.5 \cdot L_{s,i} \cdot \left(20.4 \cdot \omega_{s,i} + 1.52 \cdot \omega_{s,i} - 0.075\right)}{P_i \cdot F_v^{0.44}} \right)$$

$$F_v = \left(\frac{L_w \cdot \omega_w + L_f \cdot \omega_f + L_c \cdot \omega_c + L_s \cdot \omega_s}{5} \right)$$

with average luminance of the walls (L_w), floor (L_f), ceiling (L_c) and source (L_s) and with solid of the walls (ω_w), floor (ω_f), ceiling (ω_c) and source (ω_s).

In this study we used the evalglare-implementation of the VCP. It follows the DGR definition as described before. For the VCP calculation it uses instead:

$$VCP = \frac{50}{\sqrt{2}} \cdot \mathrm{erf}(6.374 - 1.3227 \cdot \ln DGR) + 50$$

and if DGR > 750

$$VCP = 0$$

and if DGR < 20

$$VCP = 100$$

3 Methodology

3.1 Study descriptions

The experiments for the study “**AR-DEO** and **AR-EPI**” were conducted between 2012 and 2014 in Mendoza (Argentina) [29]. On a factorial experimental design of two factors at two levels (i) chamber orientation (East, North), (ii) relative position of the workstation and window (0º or 90º), and (iii) presence/absence of solar shading device (white venetian blind), three lighting scenarios were selected: (I) East - 0° Workstation – No Shading Device; (ii) East – 90° With Shading; (iii) North – 0° No Shading Device.

The experiments for the study “**DE-DK-Ecco**” were conducted between 2003 and 2005 in Copenhagen (Denmark) and Freiburg (Germany) [10]. Three different window sizes and three different shading devices (white Venetian blinds, specular reflective blinds, foil shading) were used to create different lighting conditions. 348 of the 366 cases were used to develop the DGP metric. For this cross-validation and robustness study, the DGP-development data are excluded for any evaluation. Therefore, most of the data from the DE-DK-Ecco-Build-study were used only for the derivation (“training”) of the borderline values between the subjective glare categories of the metrics.
The experiments for the study “**DE-Quanta**” were conducted between 2008 and 2011 in Freiburg (Germany) in the same facility as in “DE-Ecco-Build” and therefore the experimental setup is very similar. The main differences are that additional shading devices were examined (fabric shading devices), the window size was fixed and that both rooms were used for the user assessments and the luminance cameras were placed besides the subject [21].

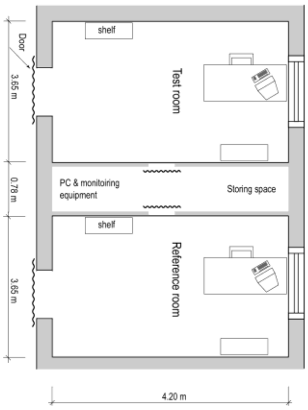
The “**DE-Gaze**” study [20] was conducted in 2013 in the same facility in Freiburg (Germany) in the same facility as in “DE-Ecco-Build”. Within this study, no shading devices were used and therefore situations with and without the sun in the field of view and with direct sunlight or presence of sunpatches in the field of view occurred.

The “**IL-DayViCE”** study was carried out between 2009 and 2011 in Israel [22]. A controlled experiment was performed at the Sde Boqer campus of Ben-Gurion University during the winter of 2010. Two nearly identical rooms alternated randomly as a reference (where measurements were made) and as a test space where subjects performed a variety of tasks. Variations of interior lighting conditions were obtained by the use of shading and light redirection devices, including white Venetian blinds, tinted glazing and light shelves (internal and external), in different combinations. The experiment also looked at the effect of different seating positions with respect to the window. Sessions were conducted only on sunny, cloudless days, characterized as a CIE Standard Clear Sky (Type 12)[48].

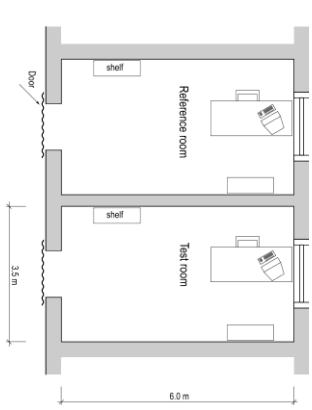
The experiments for the study “**JP-office**” were conducted in December, 2008 in Tokyo (Japan) [15]. The test room had windows facing south with white Venetian blinds. The experiments were conducted for two different positions (2m and 4m from the façade), but for this study only the data in 2m distance are used. In the experiments three different blind slat angles were applied:
1. Cut-off angle and 2. Cut-off angle +15°, 3. Cut-off angle +20°. Each condition was evaluated by three subjects simultaneously, they were seated side by side.

The study "**US-Fabric** "conducted at Purdue University in West Lafayette, Indiana, USA in 2016 aimed to investigate glare perception in the special case of the sun being within the field of view through window shades [12]. In that scope, an experiment was conducted with 14 different shading fabrics with different optical properties, in terms of openness factor (0.7%-7%) and visible transmittance (2.8% - 15.9%). Two new glare predictors were developed to address such special cases: (i) DGP_{mod}, a modification of the DGP equation aiming to address the altered balance of overall brightness and contrast induced by the extreme luminance of the sun, partly diffused through the shades, and (ii) GlareEv, an illuminance-based metric using both the total and solar direct illuminance on the eye.

Test-facilities - Layout

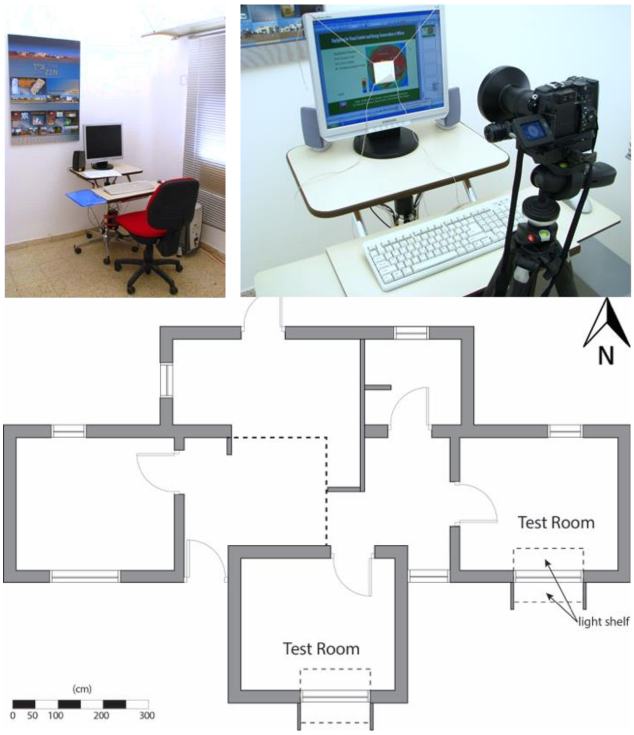
<table>
<tr><th>Test Room I: Freiburg, D</th><th>Test Room II: Copenhagen, DK</th></tr>
<tr><td>



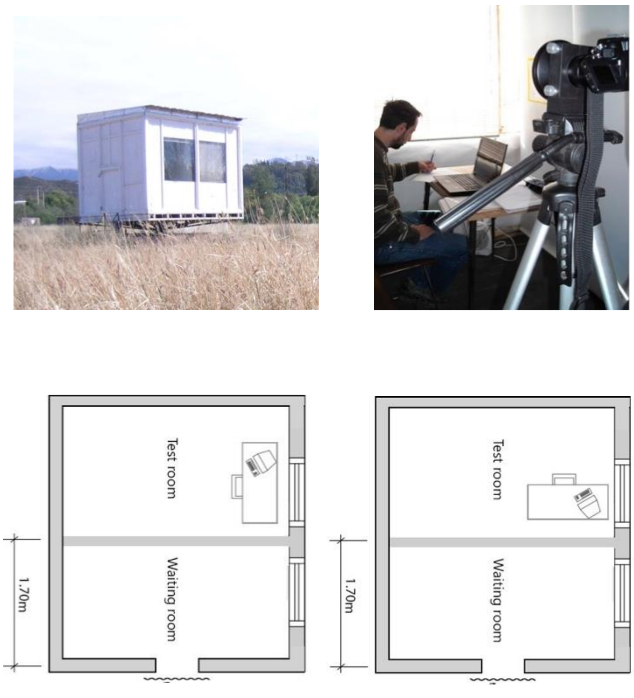
</td><td>


</td></tr>
</table>

Test Room III: Sde Boqer, ISR

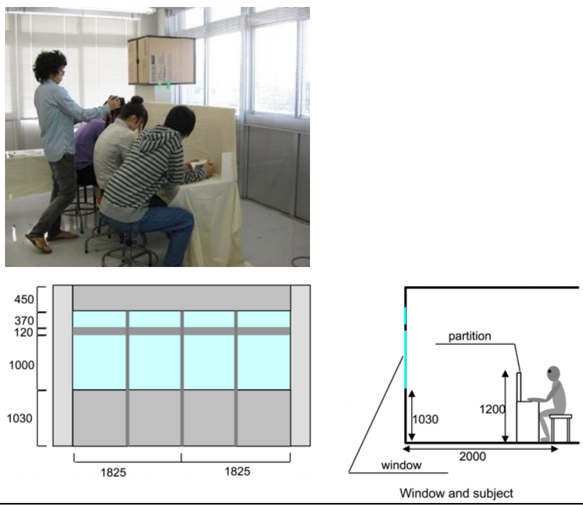


Test Room IV: Mendoza, ARG



Test Room V: West Lafayette, USA

Test Room VI: Tokyo, JP



Test-facilities - Equipment

Study-Name	Test facility No.	Place, Country	Window sizes	Shading/ Daylight systems	HDR Camera	Lens type for HDR-camera	Illuminance sensor
AR-DEO	IV	Mendoza, Argentina	S	1 x GLZ	NIKON C5400	NIK-FCE9	LMT-LUX2
DE-DK-Ecco	I II	Freiburg, Germany Copenhagen, Denmark	S M L	1 x WVB 1 x SVB 1 x TF	LMK98 LMK-M	NIK-FCE8	HGSD2
DE-Gaze	I	Freiburg, Germany	L	1 x GLZ	LMK98 LMK98C	NIK-FCE8	-
DE-Quanta	I	Freiburg, Germany	L	1 x WVB 2 x FABR	LMK98 LMK98C	NIK-FCE8	HGSD2
IL-DayViCE	III	Sde Boqer, Israel	L	1x LS 1 x GLZ 1 x TF 1 x VB	Nikon C5400	NIK-FCE9	TES-332A
JP-Office	VI	Tokyo, Japan	L	1 x WVB	NIKON D40	SIG-EX4.5	-
US-Fabric	V	West Lafayette, USA	L	14 x FABR	Canon T2i	SIG-EX4.5+ND3	KO-MIN T10

With:

S:	Small window size (glazing fraction smaller than 40% of facade)
M:	Medium window size (glazing fraction between 40%-70% of facade)
L:	Large window size (glazing fraction larger than 70% of facade)
WVB:	White venetian blinds
LS:	Light Shelf
TF:	Transparent foil system
GLZ:	Glazing without shading
SVB:	Specular Venetian Blinds
FABR:	Fabric roller shade
LMK98:	Technoteam Luminance Camera LMK98, < ±5%
LMK98C:	Technoteam Luminance Camera LMK98 Color, < ±5%
LMK-M:	Technoteam Luminance Camera LMK Mobile, < ±10%
NIKON C5400:	NIKON Coolpix 5400DLSR camera, HDR with Photosphere/hdrgen
Canon T2i:	DLSR camera, HDR with Photosphere/hdrgen
NIK-FCE08:	Nikon FCE08 fish-eye-lens, 182°, angular projection
NIK-FCE09:	Nikon FCE08 fish-eye, 190°, angular projection
SIG-EX4.5:	Sigma fish-eye-lens EX 4.5mm f2.8, 184°, equid-solidangle projection
ND3:	Kodak ND3.0 neutral density filter
LMT-LUX2:	Illuminance meter LMT POCKET LUX 2, class B, < ±10% accuracy
HGSD2:	Illuminance sensor Hagner Special Detector SD2, < ±5% accuracy
TES-1332A:	Light meter TES-1332A ±4%

3.2 Selection and correction of the HDR images

The correction of the image was applied in cases, when it was obvious that the underestimation of the sun disc was the reason for the deviation. For these cases, the luminance of the sun disk was increased so that the calculated illuminance matches the measured one by applying the evalglare –N option [42]. For the few cases, where it was obvious that only the illuminance sensor was not reliable, the HDR image stayed unchanged in the dataset. All other cases with more than 25% deviation between measured and calculated E_v were removed. The studies DE-Gaze and JP-Office had no illuminance-sensor installed besides the camera, therefore another procedure was applied to these images: The DE-gaze study had installed two high precision HDR-cameras in a 90° angle to each other[20], so that there was an 90° overlapping area for the two images. The luminance of a reference point was compared and none of the images had a deviation more than 25% on that reference point. In addition, the measured luminance of the sun was checked manually for consistency. For the JP-Office HDR-images, all images with the sun disk visible in the field of view were removed since there was an obvious pixel overflow and there was no other reliable data available to correct these images.
For the unchanged HDR images of the six datasets, bias (eq. 1), normalized bias (eq. 2), root mean squared error RMSE (eq. 3) and normalized root mean squared error NRMSE (eq. 4) are calculated

$$\text{bias} = \frac{1}{N}\sum(E_{\text{image}} - E_{\text{measured}}) \quad (1)$$

$$\text{normalized bias} = \frac{\sum(E_{\text{image}} - E_{\text{measured}})}{\sum E_{\text{measured}}} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum(E_{\text{image}} - E_{\text{measured}})^2} \quad (3)$$

$$\text{NRSME} = \sqrt{\frac{\sum(E_{\text{image}} - E_{\text{measured}})^2}{\sum E^2_{\text{measured}}}} \quad (4)$$

3.6 Dataset preparation - calculation of the metrics

The metrics are calculated using evalglare [41,42] (versions 1.20 – 2.03), a RADIANCE [43] based tool to evaluate HDR-images. Five different runs with different parameter settings were needed to extract all the information to calculate all metrics investigated for this study, as follows:

1. evalglare -T *xpos ypos size* -B 0.34907 -d -c *checkfile.hdr input.hdr*
   With this setting, sixteen of the metrics are calculated directly. The task-driven glare source detection mode [10] is used with the default threshold multiplier of 5. The task position and size were adjusted individually to the scenes.
2. evalglare –A *window_mask.hdr input.hdr*
   This setting calculates values from the window area and is needed for following metrics: L_{avg_win} , L_{med_win} , L_{std_win} and PGSV. A masking-file *window_mask.hdr* covering the window area is used.
3. evalglare –A *lowerwindow_mask.hdr input.hdr*
   This setting calculates values from the window area below 2m and is needed only for the $L_{med\_lowerwin}$ metric and uses a respective masking file.
4. evalglare -G 2 -b 2000 -d *input.hdr*
   With these command options the amount of pixels larger than 2000 cd/m^2 in Guth's [49] field of view are calculated, needed for the GSV metric.
5. evalglare -G 2 -b 0.00000001 -d *input.hdr*
   This evalglare call is used to calculate the average luminance and total amount of pixels in Guth's field of view, needed for the GSV metric.