

## New method for analyzing a luminous environment considering non-image-forming effects of light

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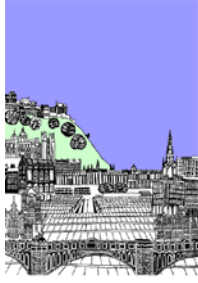
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# PLEA 2017 EDINBURGH

*Design to Thrive*



## **New method for analysing a luminous environment considering non-image-forming effects of light**

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**Abstract:** The discovery of a third photoreceptor in the human eye has shown that both, Non-Image-Forming (NIF) and image-forming effects of light, require attention in lighting design. Laboratory experiments have indicated that the direction at which light enters the human eyes may play a significant role in the magnitude of the NIF light effects due to either a non-homogenous distribution of the NIF photoreceptors across the retina or varying sensitivities of these photoreceptors.

A new method is proposed in which different retinal areas and their NIF effect's contributions are included in analysis of luminous environments. The method is implemented to assess the influence of different façade arrangements and view directions on the magnitude of NIF effects of light. The findings show a high influence of both view direction and window size on the relative luminance values received from different areas in the visual field. A hypothetical weighting factor was introduced to account for NIF-related differences in sensitivity of the different retinal areas.

**Keywords:** light directionality, human visual field, ipRGCs, daylighting, health

### **Introduction**

Retinal light exposure is essential not only for its image-forming effects which enable human beings to see and interact with their surroundings, but also for its Non-Image-Forming (NIF) effects which influence human's health and well-being. Primarily responsible for stimulation of NIF effects, is the non-rod, non-cone photoreceptor in the human eye called "intrinsically photosensitive Retinal Ganglion Cell" (ipRGC) (Berson et al., 2002; Hattar et al., 2002; Rollag et al., 2003).

The light factors influencing stimulation of NIF effects have been reviewed and categorized based on their characteristics into two groups: luminous and temporal (Khademagha et al., 2016a). Directionality of light is an important luminous light factor which has been found to play a significant role in the magnitude of NIF effects in humans (Glickman et al., 2003; Lasko et al., 1999; Visser et al., 1999; Rüger et al., 2005).

In nighttime laboratory experiments with human subjects, when directionality of light was investigated, four retinal areas have been studied: 1) superior, 2) temporal (on the ear side), 3) inferior, and 4) nasal (on the nose side). These retinal areas, relative to a point of gaze, have a reverse relationship with the visual fields e.g., the superior and nasal retinal areas correspond to respectively the lower and outer visual fields.

Nocturnal suppression of melatonin, the hormone that regulates the sleep-wake rhythm, is often chosen as a biomarker for NIF light effects in laboratory experiments with human subjects. Results of these nighttime studies have shown that illuminating the inferior (Glickman et al., 2003; Lasko et al., 1999) and nasal (Visser et al., 1999; R ger et al., 2005) retina was significantly ( $p < 0.05$ ) more effective compared to illuminating the superior and temporal retina in melatonin suppression. Based on these findings, two hypotheses were suggested: either the inferior and nasal retina are more sensitive to light stimuli when NIF light effects are concerned, or they contain a higher density of ipRGCs. To find out which hypothesis is more likely, animal studies in which either the distribution of ipRGCs or the light directionality were investigated, have been reviewed (Khademagha et al., 2016b). Regardless of differences in proposed spatial distribution of the ipRGCs, both human and animal studies have suggested an inhomogeneous distribution of ipRGCs throughout the retina.

Directionality of light has been considered in (day)lighting design and evaluations with regards to image-forming effects. However, the influence of light directionality on NIF effects has not yet been incorporated, neither in (day)lighting design nor in the evaluations. Therefore, this research proposes a method to include NIF-related differences in distribution/sensitivity of the new photoreceptors in analysis of luminous environments. The method has been implemented to assess the influence of changing ‘window size’, ‘view direction’ and ‘view position’ on the non-image-forming effects of light.

## Method

The basis for analysis were High-Dynamic-Range (HDR) images as they can capture a great dynamic range of irradiance values in real environments. The (backward) ray-tracing simulation software Radiance was used to generate HDR images for different design scenarios and to include NIF-related differences in distribution/sensitivity of the new photoreceptors in analysis of luminous environments. A standard CIE clear sky model (with -a, -o, -m, -t, and +s as input options) was used for the quantitative analysis. To account for external reflections, a ground plane with luminous reflectance of 20% (mimicking asphalt) was placed below the modeled room.

Simulations were carried out for the IEA task 27 reference office room with an adjustment in its faade design (van Dijk et al., 2003). The location was set to Eindhoven, the Netherlands ([51°26’N 5°28’E](#)). As shown in Figure 1, the reference office (dimensions 3.6 x 5.4 x 2.7 m) has a facade with a single daylight opening containing double pane low E glazing (with normal luminous reflectance of 0.1). The window is located at the South wall and is placed at the center of the wall in order to maintain/provide a view to outside. Two window sizes were used: 60% and 100% Window to Wall Ratio (WWR). The 60% WWR was chosen as it has been a recommended window size for the South orientation when both visual comfort and energy consumption are considered (Ochoa et al., 2012). The 100% WWR was chosen as representation of the wide implementation of fully glazed faades in contemporary building design.

HDR images were generated for one hour time intervals for every month on 15<sup>th</sup> day (the middle of the month). Results will be reported for three of those days: December 15<sup>th</sup> (close to least sun hours during the year), March 15<sup>th</sup> (moderate sun hours during a year), and June 15<sup>th</sup> (close to most sun hours during a year). Simulations were done for working hours between 9:00 and 17:00 local time. Angular fisheye images were generated at the occupant’s eye height in sitting position (1.20 meter from the floor) in the middle of the room and at 1.0 meter (‘close’) and 2.7 meters (‘far’) distance from the window. For each view position, two

view directions were implemented: one towards the window (South orientation) and the other one parallel to the window (West orientation).

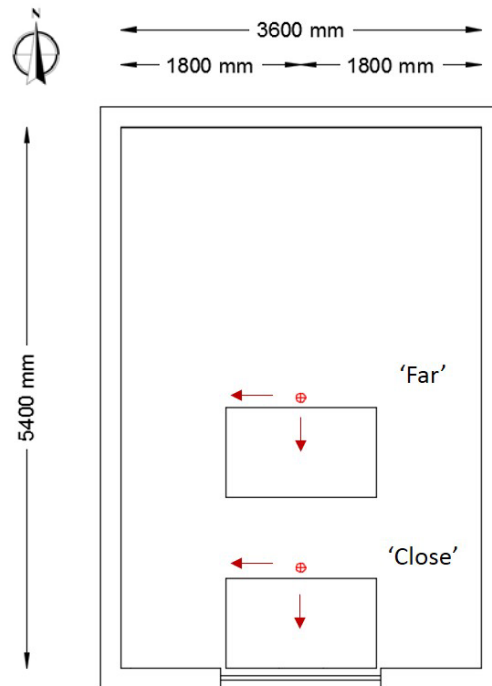


Figure 1. Floor plan of the reference office used in this study in addition to the view positions.

An example of the human visual field for both eyes reported by Lange (Lange, 2014), shown in Figure 2, was used to define different masks each corresponding to a different area in the visual field and consequently a retinal area. From four different areas in the visual field, two areas namely 'upper' and 'lower' were chosen to be investigated and used as a mask. The right-side and left-side visual fields were not studied as they overlap each other when both eyes are open.

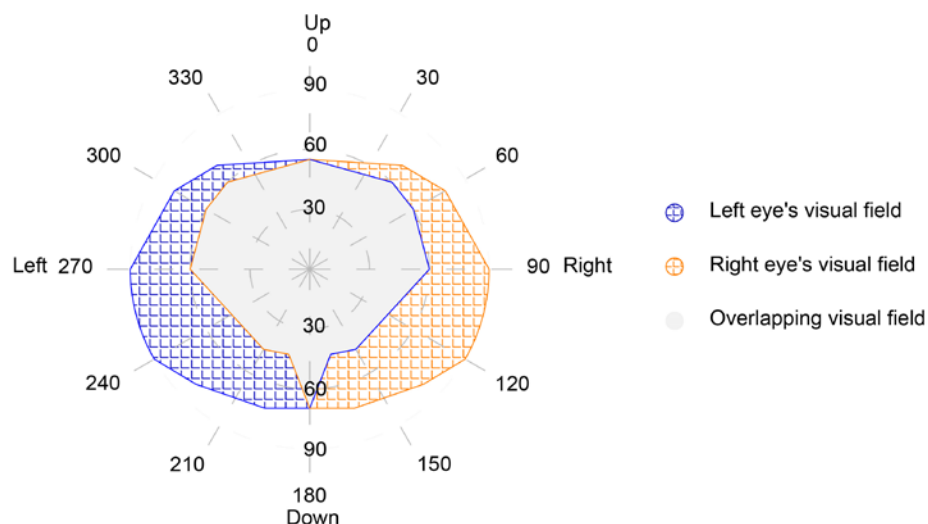


Figure 2. Human visual field for both eyes after Lange (Lange, 2014).

A TIFF image was generated from every mask using Adobe Photoshop CS6. Masks were made such that only the area that they represent was filled with white colour and the rest of

the area was covered in black. The mask image had the same size as the HDR fisheye images that were made in Radiance (X=512 and Y=512).

When NIF light effects are concerned, CIE (2014) suggested to measure radiometric quantities and weigh them by the action spectra of the desired (physiological/behavioral) effect. In this paper the aim is the comparison rather than the exact NIF effects of two retinal areas. Therefore, photometric quantities are simulated and compared. The Radiance-based tool Evalglare (Wienold et al., 2006) was used for quantitative analysis. Evalglare version 1.31 enables the application of masking in evaluation of luminous environments. The tool merges the mask and the HDR picture and gives as output the average, minimum, and maximum luminance value of the masked field. In this paper, the ratios between the average luminance values of the upper visual field compare to lower visual field are reported. Evalglare accepts mask images only in HDR format. Therefore, each TIFF mask image was first converted to an HDR image in Radiance (using `ra-tiff -r`) and then combined with HDR images generated from different design scenarios in Evalglare. Figure 3 shows an example of an HDR image and the same image when it is masked with the upper and lower visual field's masks.

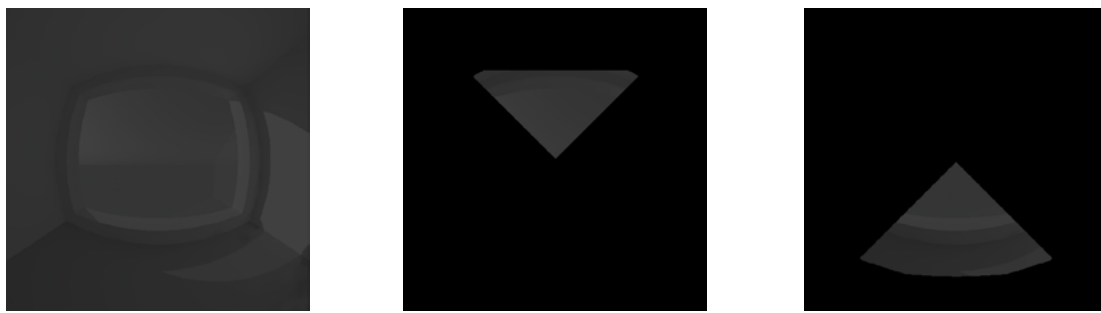


Figure 3. An example of a HDR image (WWR60%, 15<sup>th</sup> March, 9:00, and view towards South orientation, view position 'close' to the window) and the same image masked with the upper and lower visual field's masks (from left to right).

A hypothetical weighting factor was applied to account for the inhomogeneous distribution of ipRGCs over the superior and inferior retinal areas. The weighting factor was derived from Glickman's experiment (Glickman et al., 2003), in which superior and inferior retina were investigated using a helmet to restrict the retina exposure. In their experimental conditions, the superior retina exposure suppressed melatonin by ~5% while the inferior retina exposure suppressed it by ~29%. Therefore, a hypothetical weighting factor of 6 was implemented when the upper visual field was compared to the lower visual field.

## Results and discussion

Table 1 shows unweighted ratios between the average luminance values of the Upper (U) to Lower (L) visual fields for three days of the year (15<sup>th</sup> of December, March, and June) and two window sizes (WWR's of 60% and 100%), when the view direction was toward the window (South orientation) at two view positions ('close' and 'far').

Table 1. Ratios between the average luminance value of the Upper (U) to Lower (L) visual fields for three days and two window sizes, when view direction is towards the window (South orientation) at two view positions ('close' to the window and 'far' from it).

Office hours	Ratios (U/L) for view position 'close'						Ratios (U/L) for view position 'far'					
	WWR 60%			WWR 100%			WWR 60%			WWR 100%		
	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>
9:00	3.8	1.4	1.0	4.5	1.6	1.2	4.2	2.9	2.3	4.2	2.9	2.3
10:00	4.6	1.4	0.7	4.7	1.5	0.9	4.3	2.1	2.0	3.8	2.0	2.0
11:00	4.1	36.2	0.7	3.8	31.5	0.9	3.1	1.3	1.7	2.9	1.4	1.7
12:00	68.0	32.2	0.7	53.3	28.4	0.9	71.2	1.0	1.5	53.9	1.2	1.5
13:00	65.1	33.4	0.7	51.3	29.8	0.9	67.5	1.0	1.5	51.8	1.3	1.5
14:00	4.2	33.8	0.7	3.8	29.6	0.9	3.1	1.1	1.6	2.9	1.3	1.6
15:00	4.8	1.6	0.7	4.8	1.6	0.9	4.3	1.6	1.9	3.9	1.5	1.9
16:00	3.9	1.4	0.9	4.4	1.5	1.1	4.2	2.5	2.2	4.1	2.4	2.2
17:00	6.7	1.7	1.2	7.2	1.9	1.3	6.6	3.3	2.5	6.5	3.3	2.5

For the 'close' view position, the ratios are higher than 1.0 on the 15<sup>th</sup> of December and March for both window sizes. Very high ratios on these two days between 11:00 and 14:00 hours, indicate that the average luminance value of the upper visual field is much higher than that of the lower visual field which is due to the sun entering the upper field of view at these hours. The ratios, during the majority of the office hours on June 15<sup>th</sup>, are lower than 1.0, meaning that the average luminance value of the lower visual field is higher than that of the upper visual field. The reason for the ratios lower than 1.0 during those hours on June 15<sup>th</sup> is the direct radiation that reaches inside the room because of the high sun angle and that reflects up from the floor adjacent to the window.

For the 'close' view position, increasing the window size from 60% to 100% WWR increase the average luminance values for both the upper and lower visual fields, with a slightly higher increase for the upper field compared to the lower field. However, the influence of increasing window size on the ratios of the average luminance values was small and did not always increase the ratios. On the 15<sup>th</sup> of December (from 12:00 to 13:00) and March (from 11:00 to 14:00), increasing the window size decrease the ratios. The reason for such decrease in ratios is a higher average luminance value observed by the lower visual field when the façade is fully glazed. The shadowing effects caused by the walls adjacent to the window increases the average luminance's ratios for the smaller window size.

Changing the view position from 'close' to 'far' decrease the average luminance values of the upper and lower visual fields for both window sizes. The influence of changing the view position on the average luminance's ratios was substantial during some hours (from 11:00 till 14:00) in March. The reason is a large decrease in the average luminance values of the upper visual field as a result of observing a larger ceiling area in the 'far' view position compared to the 'close'.

Increasing the window size when the view position was 'far', increased the average luminance values for both upper and lower visual fields. The influence of increasing the window size on the ratios of average luminance values was small.

Table 2 shows the ratios in average luminance values of the upper to lower visual fields when view direction was parallel to the window (West orientation) at two view positions ('close' and 'far') for three days of the year (15<sup>th</sup> of December, March, and June) and two window sizes (WWR's of 60% and 100%).

Table 2. Ratios between the average luminance value of the Upper (U) to Lower (L) visual fields for three days and two window sizes, when view direction is parallel to the window (West orientation) at two view positions ('close' to the window and 'far' from it).

Office hours	Ratios (U/L) for view position 'close'						Ratios (U/L) for view position 'far'					
	WWR 60%			WWR 100%			WWR 60%			WWR 100%		
	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>	December 15 <sup>th</sup>	March 15 <sup>th</sup>	June 15 <sup>th</sup>
9:00	1.8	0.5	1.6	1.9	0.9	1.4	1.7	1.7	2.3	1.8	1.7	2.2
10:00	1.2	0.4	0.8	1.5	0.7	0.8	0.8	0.5	2.4	1.2	0.5	2.3
11:00	1.0	0.4	0.7	1.3	0.7	0.6	0.5	0.4	2.5	0.9	0.4	2.4
12:00	1.1	0.5	0.8	1.1	0.6	0.7	0.7	0.4	2.7	0.9	0.5	2.5
13:00	1.3	0.7	0.9	1.0	0.6	0.8	1.0	0.6	2.7	1.1	0.6	2.6
14:00	1.7	1.1	1.4	1.3	0.9	1.1	1.9	1.9	2.8	1.6	1.3	2.6
15:00	1.9	2.0	2.5	1.7	1.4	1.8	1.9	2.3	2.7	1.9	2.3	2.5
16:00	1.9	2.2	2.8	1.9	1.8	2.5	2.0	2.2	2.7	2.0	2.2	2.5
17:00	1.4	2.1	2.6	1.7	2.0	2.9	1.5	2.1	2.5	1.6	2.1	2.4

The ratios of the average luminance values of the upper to the lower visual fields for the West view direction are much smaller than the ratios for the South view direction for both window sizes. This is not surprising as in the West view direction mainly indirect reflected light from the West wall is observed.

Increasing the window size from 60% to 100% WWR for both view positions of 'close' and 'far' increases the average luminance values for both the upper and lower fields. However, the influence of increasing window size on the ratios was small and did not always increase the ratios. Moreover, changing the view position from 'close' to 'far' for the West view direction both increased and decreased the ratios.

All in all, comparing the ratios in different design conditions shows that luminance values in the upper visual field in most cases are higher than those in the lower visual field, while in some cases they are lower. The magnitude of both increases and decreases varies depending on the view direction, view position, time of the day, day in the year, and the window size.

To compensate for NIF-related differences in distribution/sensitivity of ipRGCs, reported ratios should be weighted using a hypothetical weighting factor. If we apply the weighting factor of 6 found by Glickman et al. for melatonin suppression (Glickmann et al., 2003), the NIF impact of the upper visual field, corresponding to the inferior retinal area, is

always higher than the NIF impact of the lower visual field (superior retinal area). Using this method one can take one step further towards including the NIF-related influence of light directionality in design of our built environment. In the next step, image-forming effects of light (i.e., visual comfort) can be investigated for every design condition. Doing so, one can define an optimized design condition in which both image-forming and non-image-forming effects of light are taken into account.

## Conclusions

A new method is proposed to include NIF-related differences in distribution/sensitivity of the ipRGCs in the analysis of luminous environments. The influence of 'window size', 'view direction', and 'view position' on the average luminance's ratio of the upper visual field to the lower visual field was investigated. Results show that the ratios can both be higher and lower than 1.0 depending on design conditions. Moreover, from the studied design conditions, view direction showed the highest influence on the average luminance's ratios.

According to literature, the inferior retina (upper visual field) is more effective compared to the superior retina (lower visual field) in stimulation of NIF effects (melatonin suppression). Therefore, a hypothetical weighting factor of 6, derived from literature, is introduced to compensate for the NIF impact of the upper to lower visual fields. As a result of implementing the weighting factor, in all studied design conditions during office hours for three days during a year, the effective ratios are higher than 1.0. Nevertheless, the weighting factor is hypothetical and is derived from nighttime studies. For a more accurate weighting factor daytime studies are needed in which the influence of directionality of light is further investigated.

The method will be expanded by including the 'spectrum' of light in the analysis of luminous environments. This is particularly important for daylight, as its spectrum changes during the day and is rich in short-wavelength part of spectrum.

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