

Retinal illuminance from vertical daylight openings in office spaces

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KEYWORDS

light, daylight, electric light, retinal illuminance, vertical illuminance, horizontal illuminance, biological stimulation effects, mood, well-being

ABSTRACT

Light entering our eyes (ocular light) not only enables us to see. It is now clear that biological stimulation via ocular light is important for our health, well-being and ability to perform. This paper presents the first results of a comprehensive research project to characterize and develop healthy office lighting that will meet both visual and biological stimulation needs.

For different working planes in a standard office room a person is simulated in an experimental set-up at eye-height (1.25m) sitting at a desk, viewing in different directions. The measurements took place for three types of lighting conditions: daylight only, electric lighting only and a combination of daylight and electric lighting.

Daylight entering through a vertical window has a very strong vertical illumination component, as opposed to a ceiling based electric down lighting system, as is widely used in offices. The ratio E_{ret}/E_{hor} is influenced mostly by daylight. In a situation with electric lighting luminaire layout and photometric distribution are important.

INTRODUCTION

Research at mainly medical institutes has shown that light entering our eyes (ocular light) not only enables us to see. There are non-visual pathways connecting our eyes with different parts of our brain, including the SCN, also known as our Biological Clock. Scientific knowledge about

the non-visual, biological stimulation effects of ocular light in humans is developing rapidly (Badia et al 1991, Grunberger et al 1993, Boivin et al 1996, Begemann et al 1997, Jewett et al 1997, Czeisler and Brown 1999, Cajochen et al 2000, Rimmer et al 2000). It is now clear that biological stimulation via ocular light is important for our health, well-being and ability to perform and that intensity, timing, dose and spectral composition of ocular light exposure are important. Lighting standards and practice in offices today are solely based on visual criteria.

Foveal vision and the required task illuminance (luminance) to see "adequate" in the traditional paperwork office have been the main determining factors for our lighting standards. The fact that we use desks and tables to work at and put our paper on has given us "horizontal illuminance on the working plane" as the dominant lighting installation design parameter. However this is not very relevant for biological stimulation where the amount of light falling on and entering the eye appears to be important. This paper presents the first results of a comprehensive research project to characterize and develop healthy office lighting that will meet both visual and biological stimulation needs.

THEORY

Since the focus of this research is on daytime office work, biological stimulation effects in our wake cycle are relevant. Not too surprising, taking into account that human evolution happened outdoors, relatively high illuminance levels have been reported (Beld, 2001) as being necessary for adequate stimulation (typically > 1000 lux).

Figure 1: Retinal Exposure Detector

Unfortunately in almost all of these studies it is not clear which illuminance level (horizontal task illuminance, vertical illuminance, eye illuminance etc) was reported and whether the values reported were in fact representative for the biological light exposure.

It is our hypothesis that as a best, first order approach the total flux on the retina is the right parameter for measuring the biological light exposure. This assumes that the biological sensors in the retina are more or less evenly distributed. These sensors still have to be found, but recent studies (Ruberg et al 1996, Brainard et al 2001, Thapan et al 2001) of the spectral sensitivity of biological stimulation suggest that the biological sensing system probably uses a combination of elements, some of which are indeed distributed over the retina. Since it is not possible to actually measure the retinal exposure we use a model of an average eye/person.

What is universally measurable and directly linked to design-parameters for the luminous environment is the vertical illuminance on the front of the eye. By measuring the horizontal task illuminance, vertical eye illuminance and retinal illuminance in various positions and viewing directions in offices with artificial- and day-light we obtain a 3-dimensional office map showing both the visual and biological “dark and bright spots”. This will provide the neces-

sary input for designing healthy luminous environments, including recommended office outlays and worker position in relation to day light entrance.

APPROACH

For different working planes in a standard office room a person is simulated in an experimental set-up at eye-height (1.25m) sitting at a desk. Behind the measuring detectors a board is located, to account for the screening effect of the part of the body above the working plane. (see Figure 3).

The retinal illuminance, $E_{retinal}$, is measured with a specially developed instrument, the Retinal Exposure Detector (Van Derlofske et al 2000). Developing the instrument data were obtained from eyes of an average person of 45 years and the pupil was assumed to have a 5 mm diameter. The total flux on the retina is influenced by two factors: the cut-off of the eye as a result of anatomic restriction and the eye’s spatial response function. A facial shield around the Detector produces appropriate cut-off angles for, in this case, a right eye (see Figure 1). When replacing the Retinal Exposure Detector by a standard, cosine corrected, detector the illuminance values at that measuring point will be higher because of the absence of the facial shield. Because in that case actually the illuminance on the face is measured, this illuminance will be called E_{facial} . Next to the Retinal Detector an extra detector is located which is not further used in this paper.

Vertical and horizontal illuminance measurements are performed with standard, cosine corrected Hagner SD2 detectors. The architectural environment is an office room with standard dimensions (6.4 x 3.6 x 2.7 m) on the top floor of a two story-high building, facing east. The measurements are made on an overcast day in February. The façade contains a vertical glazed daylight opening across the total façade width, twice interrupted by steel window posts. The façade is provided with Venetian blinds. The windowsill is at a height of 0.9 meters above the floor, see Figure 2a. The color of the walls and ceiling is white

Figure 2 (a)

Figure 2: View in the office room (a) and floor plan with placement of the light detectors (b)

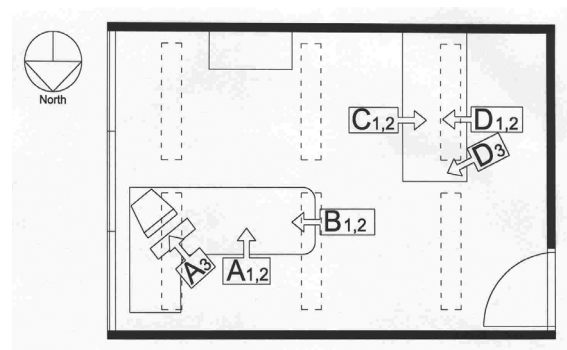
Figure 2 (b)

Figure 3 (a)



Figure 3 (b)

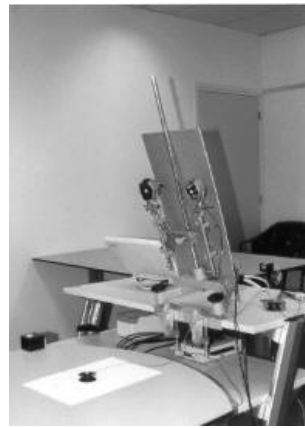


Figure 3: Experimental set-up: facing straight ahead (a) and facing 25° downward (b)

($r=0.85$) and the carpet on the floor is mixed blue-green ($r=0.09$). The large desk in front of the window and the table at the back has a light gray desktop ($r=0.46$). Other furniture in the room is a black with yellow cupboard and chairs with blue seats. The electric lighting in the office exists of three rows with each two recessed twin lamp (T5) luminaires with mirror optics, located parallel to the façade (see Figure 2).

The measurements took place for three types of lighting conditions: daylight only (overcast, no direct sun), electric lighting only (measured in the evening and with blinds closed) and a combination of daylight and electric lighting (overcast, no direct sun).

There are several measuring positions in the room (see Figure 2b). Position A is located at the desk and facing three directions: straight ahead parallel to the window (A1), inclined forward as for reading/writing (A2) and 45° turned to the window as for doing a computer task (A3) (straight forward). At the end of the desk position B is located. Here are the measuring directions straight ahead

perpendicular to the window (B1) and down (reading/writing) (B2). Often there is a workspace for conversations in the back of an office room. People sit here mostly at both sides of the table. One person is talking or reading with his/her face directed to the back wall (position C1 and C2) and another person faces the window (position D1) or reads (D2) or talks to a third person to the left (D3).

If the person is reading or writing the head is inclined forward circa 25° (Navvab et al 1997), $\gamma = 25^\circ$. If the person is facing straight ahead $\gamma = 0^\circ$ (see experimental set-up in Figure 3).

RESULTS AND DISCUSSION

Because daylight changes continuously all measured results for E_{facial} and $E_{retinal}$ are divided by the horizontal illuminance (E_{hor} horizontal desk), on the task position on the desk (in front of the simulated person, see Figure 3), to make all results comparable. It was not possible to measure all positions simultaneously because of an experimental

Table 1.

Daylight	Pos	E_{facial} [Lux]	$E_{hor(1)}$ [Lux]	$E_{fac}/E_{hor(1)}$ [-]	$E_{retinal}$ [Lux]	$E_{hor(2)}$ [Lux]	$E_{ret}/E_{hor(2)}$ [-]
	A ₁	608	699	0.87	390	713	0.55
	A ₂	449	640	0.70	293	655	0.45
	A ₃	1353	675	2.00	1179	662	1.78
	B ₁	823	731	1.13	779	748	1.04
	B ₂	392	394	0.99	381	401	0.95
	C ₁	80	532	0.15	69	546	0.13
	C ₂	72	559	0.13	53	473	0.11
	D ₁	261	571	0.46	224	554	0.40
	D ₂	238	553	0.43	226	535	0.42
	D ₃	249	573	0.43	222	546	0.41

Table 1: Results of horizontal, vertical and retinal illuminance and ratios E_{fac}/E_{hor} and E_{ret}/E_{hor} for the daylight situation. NOTE: E_{fac} & $E_{hor(1)}$ and E_{ret} & $E_{hor(2)}$ are not measured simultaneously for each position

Table 2

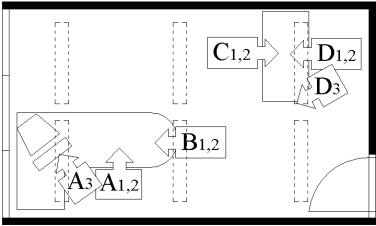
Electric lighting	Pos	E _{facial} [Lux]	E _{hor (1)} [Lux]	E _{fac} /E _{hor (1)} [-]	E _{retinal} [Lux]	E _{hor (2)} [Lux]	E _{ret} /E _{hor (2)} [-]
	A ₁	341	799	0.43	249	800	0.31
	A ₂	288	802	0.36	226	802	0.28
	A ₃	389	798	0.49	238	798	0.30
	B ₁	335	813	0.41	202	814	0.25
	B ₂	253	810	0.31	209	811	0.26
	C ₁	386	813	0.47	251	812	0.31
	C ₂	296	809	0.37	161	809	0.20
	D ₁	333	804	0.41	188	804	0.23
	D ₂	222	808	0.27	195	807	0.24
	D ₃	311	806	0.39	178	805	0.22

Table 2: Results of horizontal, vertical and retinal illuminance and ratios E_{fac}/E_{hor} and E_{ret}/E_{hor} for the situation with only electric light. NOTE: E_{fac} & E_{hor (1)} and E_{ret} & E_{hor (2)} are not measured simultaneously for each position

Table 3

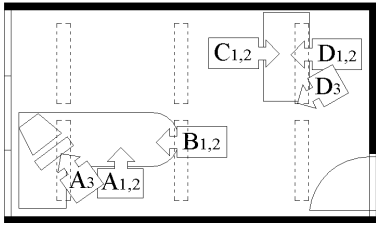
Daylight and electric lighting	Pos	E _{facial} [Lux]	E _{hor (1)} [Lux]	E _{fac} /E _{hor (1)} [-]	E _{retinal} [Lux]	E _{hor (2)} [Lux]	E _{ret} /E _{hor (2)} [-]
	A ₁	735	1289	0.57	494	1280	0.39
	A ₂	612	1236	0.50	401	1240	0.32
	A ₃	1235	1239	1.00	1039	1262	0.82
	B ₁	1008	1352	0.75	863	1343	0.64
	B ₂	878	1330	0.66	820	1327	0.62
	C ₁	475	1363	0.35	373	1361	0.27
	C ₂	394	1406	0.28	240	1426	0.17
	D ₁	605	1402	0.43	437	1378	0.32
	D ₂	465	1345	0.35	463	1425	0.32
	D ₃	524	1342	0.39	385	1319	0.29

Table 3: Results of horizontal, vertical and retinal illuminance and ratios E_{fac}/E_{hor} and E_{ret}/E_{hor} for the situation with both daylight and electric lighting. NOTE: E_{fac} & E_{hor (1)} and E_{ret} & E_{hor (2)} are not measured simultaneously for each position

restriction (amount of detectors). For that reason ratios (E_{ret}/E_{hor} and E_{fac}/E_{hor}) are used for comparison.

In Table 1, Table 2 and Table 3 E_{horizontal} desk is subdivided into E_{hor (1)} and E_{hor (2)}. E_{hor (1)} is measured simultaneously with E_{facial} and E_{hor (2)} with E_{retinal}. Because a standard detector to measure E_{facial} replaces the Retinal Exposure Detector, the illuminances E_{fac} & E_{hor (1)} and E_{ret} & E_{hor (2)} are not measured simultaneously for each position.

Daylight only

The measurements for the different positions and viewing angles are given in Table 1, for daylight only. In this table the values for E_{horizontal} desk diverge because of the variability of daylight.

The Retinal Exposure Detector is simulating a right eye, which means the facial shield screens a part of the light coming from the left. By replacing the Retinal Exposure Detector by a standard detector the blockade by the shield is eliminated. Comparing ratio E_{ret}/E_{hor} to E_{fac}/E_{hor} shows an increase from 0.55 to 0.87 in position A1 and

from 0.45 to 0.70 in position A2. In situation A3 a person facing the window at an angle of 45° receives almost a factor two more light on the retina compared to the amount reaching the desk (E_{ret}/E_{hor} = 1.78).

The retinal illuminance at the end of the desk (position B1 and B2) is almost equal to the horizontal illuminance on the desk. This is valid for both the position straight ahead and inclined position.

Although the amount of light on the table is the same, the illuminance on the retina differs considerably between the positions C and D at the table. The person facing the back wall (position C) just receives almost one third of the light in comparison to the person facing the window (position D).

Electric lighting only

In Table 2 for electric lighting only the measurements for the different positions and viewing angles are given. Although the electric lighting creates a constant illuminance level on the desk, all measured results for E_{facial} and E_{retinal} are divided by the horizontal illuminance on the desk

in front of the person to make them comparable with each other and with results in the daylight situation.

The preset for the electric lighting creates a constant average illuminance level on the desk (800 lux, see Table 2). The position of the eye differs according to both the task the person is doing and the changing position in relation to the luminaires. Because the luminaires are placed in the ceiling, the light is mainly coming from above. The ceiling based luminaires give a narrow photometric distribution.

Position A is right between two luminaires. In this position facing straight ahead (A1) or an inclination forward (A2) makes less difference for the retinal illuminance (Eret/Ehor from 0.31 to 0.28). Turning from position A1 to A3 causes a little increase in facial illuminance because of the turn towards the luminaire. The retinal illuminance stays equal because the facial shield of the Retinal Exposure detector screens the extra light from above.

Position C shows the importance of place and type of the luminaires. In position C1 the facial shield of the Retinal Exposure Detector screens a part of the light from above and Eret/Ehor ratio is 0.31 while the Efac/Ehor is 0.47. Inclination forward (C2) prevents a part of the light to fall on the facial detector so Efac/Ehor decreases to 0.37. Although the facial shield already screened a lot of light in position C1, in position C2 the Eret/Ehor is much lower (0.20).

Positions B and D give identical ratios because the location in relation to the luminaires is the same. The straight-ahead and inclined position both gives low Eret/Ehor ratios.

In general, in the situation with only electric lighting the amount of light on the retina is a quarter of the horizontal illuminance on the desk.

Both daylight and electric lighting

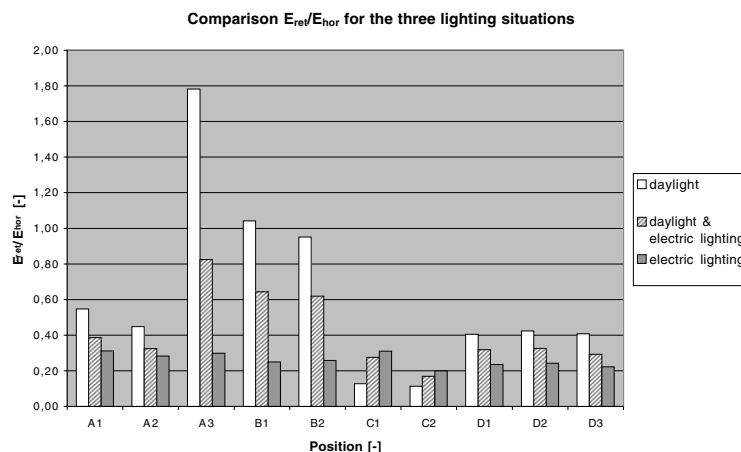
The measurements for the different positions and viewing angles are given in Table 3, for the combination daylight - electric lighting. Like the situation with daylight only or electric lighting only all measured results for Efacial and Eretinal are divided by the horizontal illuminance on the desk in front of the person to make them comparable with each other and with the other situations.

The preset for the electric lighting creates an average illuminance level of 800 lux on the desk. Daylight contribution averages out at 450-600 lux.

In position A the facial shield screens a part of the light coming from the left. Comparing ratio Efac/Ehor to Eret/Ehor shows a decrease from 0.57 to 0.39 in position A1. Inclination forward causes also a decrease (from 0.50 to 0.32). Turning from position A1 to A3 means a better position in relation to both daylight and electric lighting distribution. Turning causes for Efac/Ehor an increase from 0.57 to 1.00 and the Eret/Ehor ratio increases from 0.39 to 0.82.

Position B is located right under a narrow photometric distributing luminaire. In position B1 the facial shield of the Retinal Exposure Detector screens a part of the light from above and Eret/Ehor ratio is 0.64 while the Efac/Ehor is 0.75. Inclination forward (B2) prevents a part of the light to fall on the facial detector so Efac/Ehor decreases to 0.66. Although the facial shield already screened a lot of light in

Figure 4



Comparison between three lighting conditions for the ratio Eret/Ehor

position B1, in position B2 the Eret/Ehor is a little lower (0.62). However the daylight influence is large in position B so there are almost equal ratios for Efac/Ehor and Eret/Ehor.

Again, position C shows the importance of place (and type) of the luminaires. In position C the silhouette screens the light from the luminaire behind the set-up. In the position straight ahead (C1) both ratios are low (Efac/Ehor = 0.35, Eret/Ehor = 0.27). Inclination forward (C2) prevents a part of the light to fall on the facial detector so Efac/Ehor decreases to 0.28. Because of the facial shield in position C2 the Eret/Ehor is much lower (0.17).

In position D the influence of the daylight is still there, although the distance to the window is large.

Comparing the three lighting conditions

Comparing the ratio Eret/Ehor for the three lighting situations (daylight, electric lighting and both) shows a large daylight contribution in position A and B in the room; see Figure 4.

The parameter 'horizontal illuminance on the working plane' is commonly used in lighting installation design. However Figure 4 shows for the daylight situation that the amount of light entering the human eye is not proportionally related to this parameter. Especially in the neighborhood of the window the retinal illuminance fluctuates. Also in a position turned away from the daylight opening (position C) the horizontal illuminance on the desk is not representative for the illuminance on the retina.

CONCLUSIONS AND FUTURE PERSPECTIVE

- Daylight entering through a vertical window has a very strong vertical illumination component, as opposed to a ceiling based electric down lighting system, as is widely used in offices.
- The ratio Eret/Ehor is influenced in the window zone (position A and B) mostly by daylight

- To receive a large amount of light on the retina facing the window is favorable, even for a person sitting in the back part of the room (position D)
- Irrespective of position or viewing direction in situations with electric lighting the ratio Eret/Ehor almost remains the same in contrast with daylight situations.
- The amount of light entering the human eye is not proportionally related to the parameter 'horizontal illuminance on the working plane'.

In future experiments will be extended to different office types, office rooms on other orientations, different periods of the year and with different weather types.

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