SIMULATION OF VISUAL AND THERMAL COMFORT RELATED TO DAYLIGHTING AND SOLAR RADIATION IN OFFICE BUILDINGS

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ABSTRACT

The research we develop consists in evaluating "radiative comfort" during no heating periods in dwelling space and particularly in office buildings. The expression "radiative comfort" is used to characterize the thermal and visual component of the feeling of people set in indoor environments submitted to sky and sun irradiation by bay windows.

Two numerical models, one for the visual aspect (Genelux) and the other for the thermal aspect (TRNSYS), have been connected together to carry out simulations on radiative comfort in office buildings. From the analysis of these results, we present :

- ***the time evolution study of visual and thermal discomfort situations***. It shows that discomfort glare due to daylighting always anticipates overheatings related to direct and diffuse solar radiation;
- ***the reduction of overheatings resulting*** of a prior modification of the window's transparency based only on visual constraint;
- ***the implicit relationship between visual and thermal aspects in radiative comfort***. Hence, visual parameters only could be used as a means for maintaining both visual and thermal components within acceptable limits;
- ***the possibility to detect radiative discomfort situations*** from easy measurements of illuminances, which are the foundings of a « glaremeter » based on a simple measurement concept. Associated with a measure of operative temperature, it could constitute a complete but cheap metrological system of radiative comfort.

1. INTRODUCTION

Most scientific works have been devoted to the thermal component of human comfort but the visual component has been mainly examined for artificial sources and far less for windows. To our knowledge, both aspects involved in the "radiative comfort" expression have not so far been taken into account together.

First we collected the main notions enabling the characterization of thermal and visual comfort, then we chose to model thermal and visual phenomena. Indeed we did not make the choice of an experimental approach which would have required a very important metrology. Such an approach would not have either allowed to take easily into account the main varying cases of the study.

In the simulation, thermal comfort is evaluated by PMV factor and the visual feelings are obtained from Cornell glare index. A parametric analysis has been made for a single oriented office room and for different positions of observers.

2. PARAMETERS TO CHARACTERIZE DISCOMFORT OCCURRENCE

2.1 Visual comfort

Visual comfort can be associated to the absence of glare. The glare phenomena is due to the presence of excessive luminances in the field of view by comparison with the adaptation luminance controlling the aperture of the eye pupil. According to the great difference between these luminance values, glare can be shared into two components :

- the uncomfortable (or discomfort) glare associated to the heterogeneity of luminances in visual field and which leads in the end to an eye strain because pupilary activity increases;
- the disturbing glare which is due to excessive diffusion of light in the eyes. Visual performance is then reduced.

In daylighting, the disturbing glare which is mainly due to the sun and the circum-solar area is more detrimental to visual comfort than the uncomfortable one. Nevertheless, in such conditions, the discomfort glare (due to the heterogeneity of the sky vault luminances) alawys appears first. Consequently if discomfort glare occurrences are controlled and avoided by a bay window occultation, visual comfort will be guaranted.

Many indices have been studied to characterize uncomfortable glare. Most of them have been proposed for small dimension light sources and more particularly for artificial light sources. Our bibliographic researches induced us to take a large interest in experimental studies dealt by the Building Research Establishment in U.K. and the Cornell University in U.S.A. [1]. These studies were carried out to evaluate discomfort glare produced by bay windows and arose from variable luminances of the sky vault. Following these experiments, the Cornell glare index was defined (formula 1) for a bay window divided into m natural light sources by specific spatial discretization.

$$G = 10 \log_{10}\left[\frac{1}{L_b + 0{,}07.\Omega_w^{0{,}5}.Lw}.\sum_{i=1}^{m} L_i^{1{,}6}.\frac{\omega_i^{0{,}8}}{p_i^{1{,}6}}\right] \quad (1)$$

- m : number of sources in the visual field of the observer
- L_i : luminance of each source (cd.m^{-2})
- ω_i : solid angle subtended by each source from the eye of the observer
- p_i : GUTH position index of the source which takes into account the variation of the eye reaction in function of the position of the light source image on the retina [2]
- L_b: surround luminance or adaptation luminance (cd.m^{-2})
- Ω_{wt} : solid angular subtended by the entire bay window
- L_w :average luminance of the m sources (cd.m^{-2})

If an excessive localised sunlight occurs in a part of the window , it will be taken into account in the formula (1)
A perception scale of discomfort glare is related to Cornell index as shown in Table 1.

Glare perception	Glare index G
Just imperceptible	16
Just acceptable	20
Just uncomfortable	24
Just intolerable	28

Table 1. Connection between glare perception and the associated index

In order to comply with visual comfort, we suppose in this study that "G" glare index must be less than 24 (uncomfortable glare perception limit).

2.2 - Thermal comfort

Thermal comfort is achieved by balancing the heat gains and losses of the human body, while controlling the environmental conditions (i.e. temperature, humidity,...). The human body adjusts its functions accordingly (for instance through perspiration) and responds of the prevailing environmental conditions.

Among the various models and suggestions for the quantitative estimation of thermal comfort, the most widely used one is the one suggested by FANGER [3]. Consequently empirical comfort indices have been defined, for example the predicted mean vote PMV (2) of a large group of subjects according to a thermal psychological scale (see table 2)

$$PMV = [0{,}0303 \exp(-0{,}036\, M) + 0{,}028]\, S \quad (2)$$

with M : metabolism of the human body related to the activity (W.m^{-2})
and S : thermal load of the human body resulting of its thermal balance with environment(W.m^{-2})[3]

The formula (2) is only valid in steady state and for moderate environmental conditions

thermal perception	PMV threshold
Cold	-3
Cool	-2
Slightly cool	-1
Neutral	0
Slightly warm	+1
Warm	+2
Hot	+3

Table 2. Connection between thermal perception and the associated index. Thermal comfort correspond to $-0.5<PMV<0.5$

3. DAYLIGHT AND THERMAL MODELING

3.1 Visual aspects

Visual phenomena and particularly parameters of Cornell’s formula have been computed using the lighting simulation programme Genelux [4] developed at LAboratoire des Sciences de l'Habitat of l'Ecole Nationale des Travaux Publics de l'Etat in Lyon (France). This software allows the simulation of the propagation of radiative energy through a transparent medium using a forward ray-tracking technique. Each ray carries energy in a given wavelength range. When a ray hits a specular surface, it is generated in the appropriate directions for reflection and transmission using the fundamental optic laws. When a ray falls on a light scattering surface, the primary ray is broken down into secondary ones with appropriate amount of energy, and the new rays are regenerated using a Monte carlo technique.

3.1.1 Daylight sources : sky data productions

In daylighting, skies are characterized by their luminance distributions. Correlations have been proposed to establish most typical sky luminance distribution as a function of *usua*l climatic informations (global and diffuse irradiance, location of sun in the sky, latitude, dry bulb and wet bulb temperature) [5]. We used this algorithm to produce hourly average skies which are divided in two categories :

- for diffuse light (Fig. 1), the sky vault is divided into 13 patches which respect the main part of such sky (strip in the horizon, spherical cap on zenith and another strip for the rest of the sky),
- for direct sunlight (Fig. 2), the model requires 60 sky patches to generate equivalent sky luminances only due to the path of the sun.

Meteolux, [6] which is the name of the sky data processor, produces for each hour 13 values of luminance of the sky vault and one value of luminance corresponding to the sky patch which includes the sun. Such a processor uses a luminous efficacy model [7] to product luminous data from energetic ones which are currently available.

3.1.2 Indoor daylighting computations with Genelux

Two phases can be mentioned :

- on one hand, luminous parameters, as luminance distribution in the visual field, and several characteristic illuminances are computed inside and outside the test cell. The spatial distribution of the sky luminance is taken into account thanks to directional daylight factors [8] which allow to obtain the relative contribution of each patch of the sky separately. The results are then adjusted, considering given meteorological data, to compute the values of the parameters corresponding to the contribution of the real luminance of each patch of the sky [12].
- on the other hand, parameters must be determined to compute glare indices (solid angles, Guth position index, incidence angles, size of grids...). They mainly depend on the configuration of the test cell, on the position of the reference observer and finally on the bay windows.

3.2 Thermal aspects

A lot of software tools exist to compute thermal phenomena. We lead our investigations using TRNSYS software [9], because of its *versatility* and its easy use. Its modular conception allow to develop specific applications and to improve existing ones; for instance a comfort model has been developed and the detailed zone model used to compute thermal phenomena in the test cell has been improved in two main points :

- on one hand, we have modified the radiative exchanges by using Gebhart method [10] to take into account the long wave radiation between grey surfaces.
- on the other hand, we improved the modeling of windows considering the real photometry of their glasses.

4. SIMULATIONS

4.1 Software environment

Using the numerical models described above, parametric studies have been carried out for a test cell fitted out with a large bay window [11] [12] (Fig. 3).

Simulations were realized concurrently with Genelux and TRNSYS and allow us to study an hourly time evolution of several physical parameters (visual and thermal parameters as temperatures, energy and luminous fluxes,...).

Imputs are devided in two categories (Fig. 4) :

- First, specific thermal and visual parameters are allocated respectively to TRNSYS and Genelux.
- Then, common imputs which are related to the building data and the meteorological energy data.

From a visual modeling point of view, three main processors must be activated (Fig. 4) :

1. Meteolux, which is a luminous efficacy model (see § 3.1.1), compute luminous luminances of the sky vault from energetic data.
2. Genelux, which is the main processor, compute the illuminances repartition in the test cell using a forward ray-tracking (see § 3.1)
3. At last, Conforlux calculate, on one hand, hourly G glare index and, on the other hand, the transmission factor of the window in accordance with the threshold value $G < 24$ [12].

4.2 Evolution of thermal and visual parameters versus time

The graphs of figure 5 and figure 6 give an example of the evolution of the physical values versus time.

The chosen meteorological data correspond to a Test Reference Year from Mâcon station in France.

The following results concern a reference observer who remains seated in the middle of the room in front of the window (Fig. 3).

4.2.1 Thermal parameters

We notice on the figure 5 that the delay between inside air temperature and global horizontal irradiance is around four hours, when it is only around one hour between inside and outside air temperature. The first delay come from internal thermal inertia provided by the envelope elements located on the inside part of the walls and floors which act on radiative inputs going through the windows. In our case this internal inertia is important and the *radiative* energy coming from the sky and the sun is well stored before to be *released* by convection to the inside air. The second delay is

lower because the thermal inertia which have an effect on the thermal response is not the same. In this case all the envelope contributes to this global inertia but the ventilation rate leads to reduce the amount of its effects. Even if the global inertia is important, the final result corresponds to a low inertia.
The main radiant temperature is just above the air temperature and follows practically the same time *evolution*. This behaviour is due to the important internal thermal inertia which is rather a good solution to avoid passive overheatings of large amplitude.

4.2.2 Visual Parameters

Figure 6 shows the variation of four different illuminances versus time for a sunny day in June. Each illuminance results from the both influence of the direct luminous radiation of the sky and the sun through the window and of the interreflexions inside the room :

- Eh is the horizontal illuminance at the point 4 *of the figure 6* and at a height of 0,85 m;
- Ev is the vertical illuminance at the level of the eyes of the observer 4 *at a height of 1,20 m;*
- Emnd is the vertical illuminance on the north wall in front of the window *at a height of 1,20 m;*
- Evit-int is the vertical illuminance on the inside surface of the window. It is produced only by the interreflexions inside the room because the receiving surface cannot "see" the sky .

We notice that all these illuminances are all nearly concomitant with the global solar radiation *represented on the figure 5.* The evolution of Eh and Ev are almost identical because, at the point 4 :

- the parts of the sky seen from an horizontal surface element at 0,85 m *height* and from a vertical surface element at 1,20 m *height* are similar;
- and the corresponding solid angles projected on the receiving surface are almost the same.

However, the vertical illuminance has a smoother evolution because it is less influenced by the direct radiation from the sun *than the horizontal illuminance*.

4.3 Interactions between visual and thermal component

The following stage of the work consists in studying frequencies and interactions between computed thermal and luminous phenomena. The results allow *us* to say that visual discomfort situations appear more frequently than thermal discomfort and that visual phenomena always anticipate thermal ones as it is shown in the temporal evolution of discomfort index (Fig. 8). On the figure 9, we can also mention the time delay of two hours between visual parameters like illuminance levels and thermal parameters as air temperature.
Afterwards, the results presented above induce us to take into account the influence of the window's transparency on thermal parameters basing the computation of the glazing transmission factor on a visual constraint (G < 24). The simulation method is described in figure 4 by the broken line part in the organigram. We can see on figure 9 the evolution of the air temperature in the room. First without any modification of the window's tranparency (Ta ref). Secondly with the modification described above (Ta mod). The overheatings are reduced of about 5°C.
It is a proof that a judicious modification of the transparency of the bay window from visual comfort criteria can have, some hours later, a beneficial effect on thermal comfort.

4.4 Secondary parameters

After studying temporal evolution of some "primary parameters" of radiative comfort (PMV, air temperature, G, luminance,...) which define radiative comfort, we looked for expressions of the comfort indexes only based on « secondary parameters » as operative temperature and illuminances. Such parameters are supposed to be more convenient to measure than those included in the formula (1) and (2)

4.4.1 Visual aspects

The discomfort glare could be approached by the following semi empirical expression :

$$G' \cong a \cdot \ln\left[\frac{(En)^x}{Ed}\right] + b \qquad (3)$$

The numerator En and the denominator Ed in the argument of the logarithm of the expression (3) are two particular illuminances which are easier to measure than luminances as those of the formula (1). These two particular illuminances could be the illuminances studied in the paragraph 4.2 or others. In fact, we have to analyse the quality of different correlations between glare index G and secondary parameters as illuminances or ratio of illuminances.
At the present time,several correlations have been found. One of the best is shown on the *figure 10*. E_n and E_d corresponding to the vertical illuminances on both side of the window.

4.4.2 Thermal aspects

A similar approach has been led to find how to compute PMV index which normally needs several parameters to be determined as air temperature, radiant temperature, air velocity, humidity ratio.

In moderate indoor climates some of theses parameters, as humidity and air veloocity, don’t vary a lot. In such conditions we found that operative temperature was well correlated to PMV as shown in figure 11. This correlation is only valid for clothing and metabolism fixed at the values of the figure 11 which correspond to an office building in summer.

5. CONCLUSION

Parametric exploitations described above has been extended to other test cells with other size and other orientation of the bay window.
The results are in good agreement with those presented here in this paper.
Other investigations are being made with the aim to comfirm the simple correlations already obtained between comfort indexes and secondary parameters. This semi-empirical approach is based on the research of the better correlations with easy meseaured secondary parameters.

So, we will be able to characterize the radiative comfort of the indoor environment of office building, resulting from the influence of daylighting and solar radiation, with a simple and cheap metrologic system that could be subsequently industrialized.
Such a system could be integrated in a control chain of a bay windows occultation system in order to avoid glare and hoverheatings in office buildings equipped with large bay windows.
Our first results lead to design a metrologic system based on a simple "glaremeter" able to measure only two illuminances. One of them, at least, must be measured inside the roons to have an useful information in order to stop an active phase of the control chain when inside daylight illuminances levels become insufficient. This solution prevents to switch on artificial lighting when favourable outside daylighting conditions occur.
A measure of the operative temperature can complete the previous system to be always sure of the control of overheatings due to solar radiation. However, it is not mandatory because simple luminous informations (as illuminances) are sufficient to prevent radiative thermal discomfort if a previous calibration or/and an on-line adjustment of the apparatus is realized.

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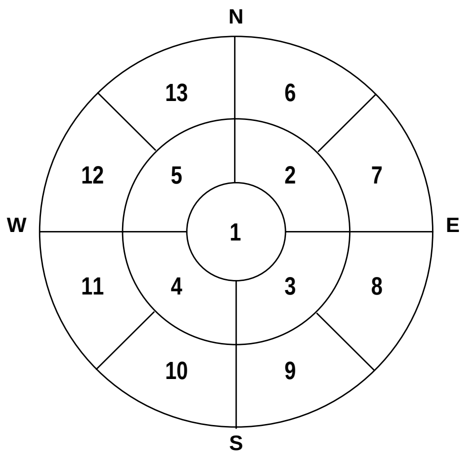

Fig. 1: 13 grids for diffuse sky

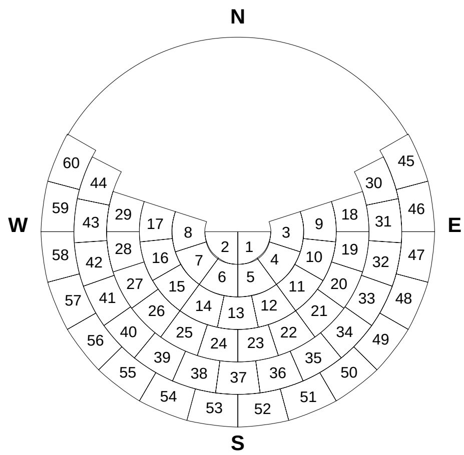

Fig. 2: 60 grids for sunlight

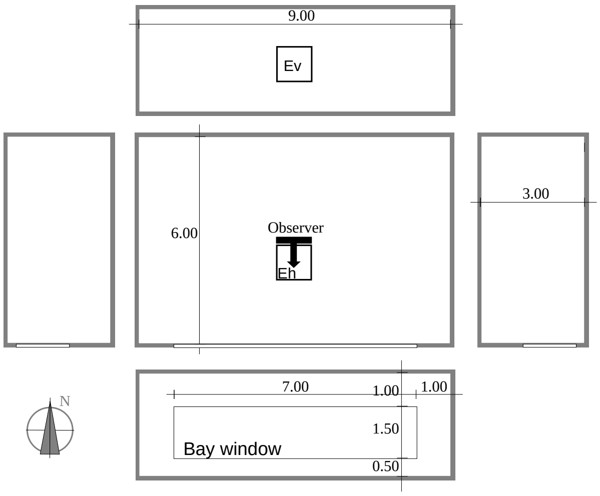

Fig. 3: Test cell plan

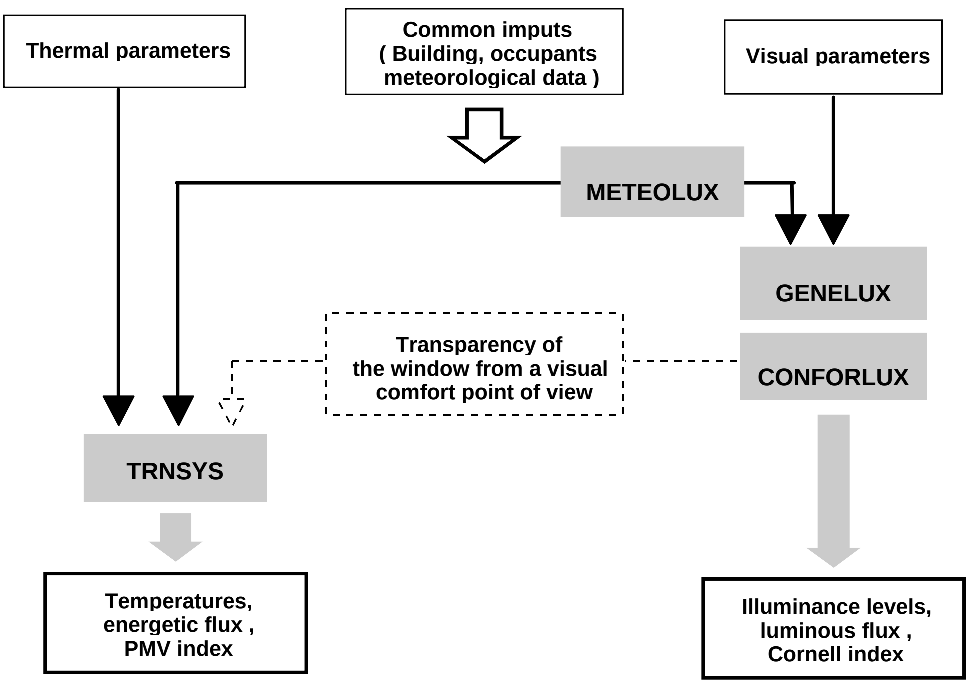

Fig. 4: Simulation organigram

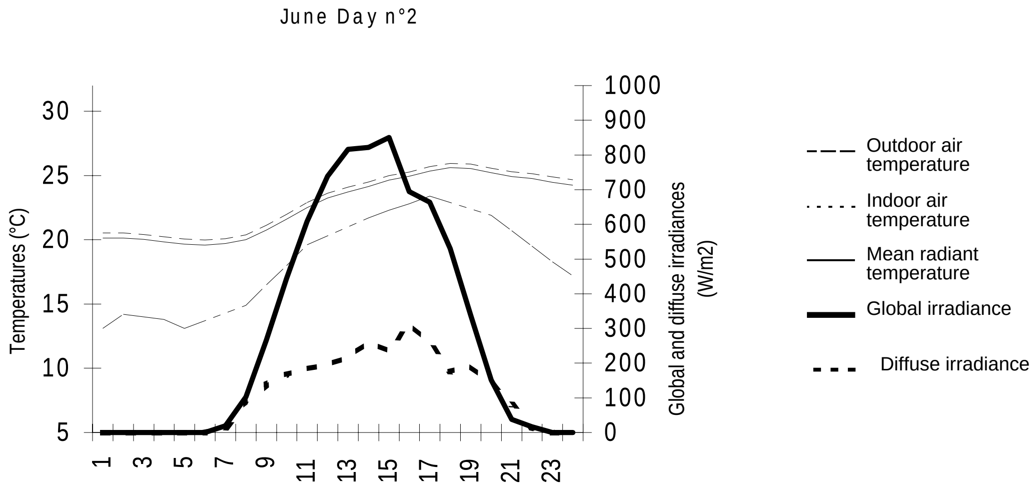

Fig. 5 : Evolution of thermal parameters versus time

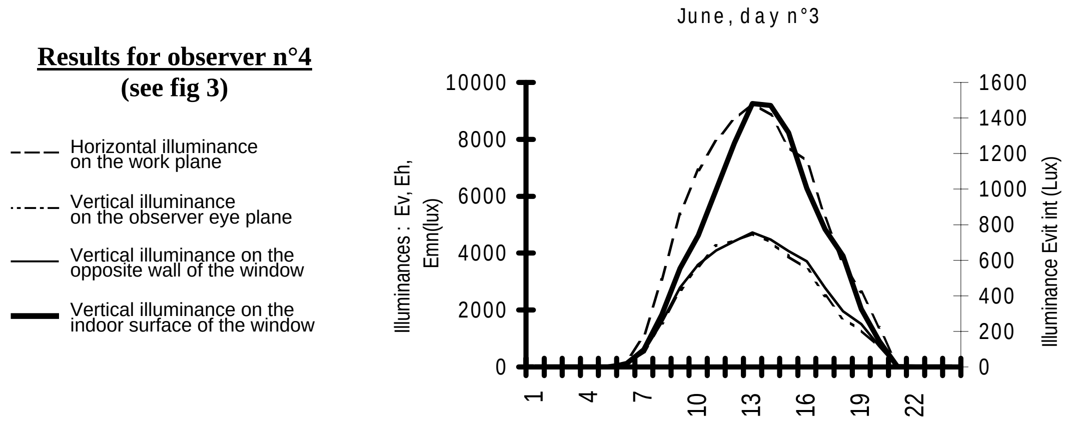

Fig. 6: Evolution of luminous illuminances versus time

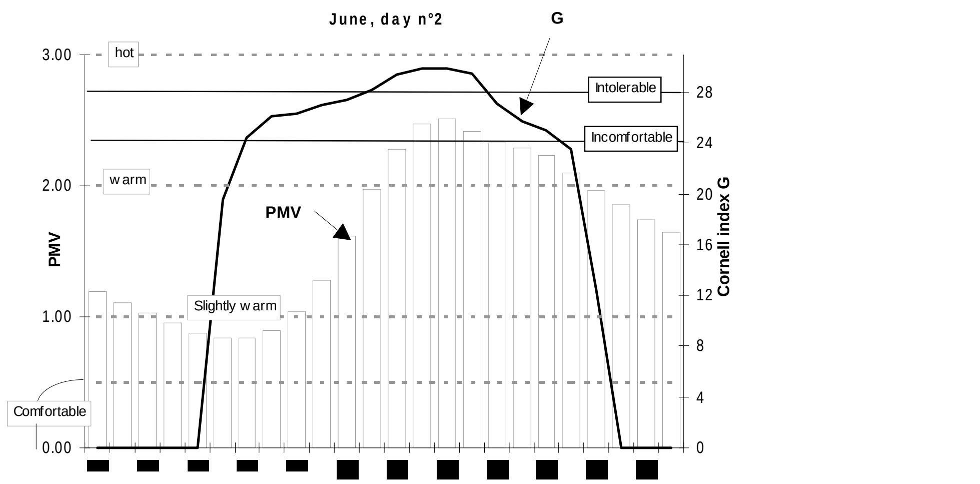

Fig.7: Visualization of the time evolution of Cornell glare index G and PMV showing a delay of more than four hours

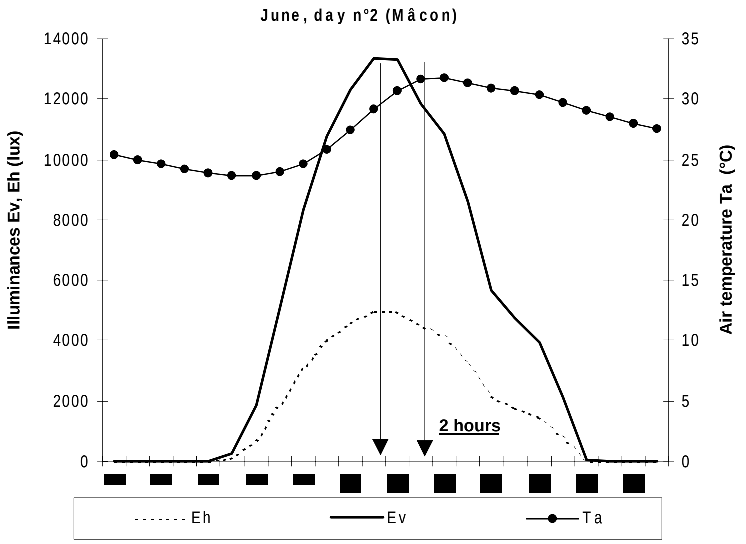

Fig. 8: Visualization of the delay between thermal and visual parameters

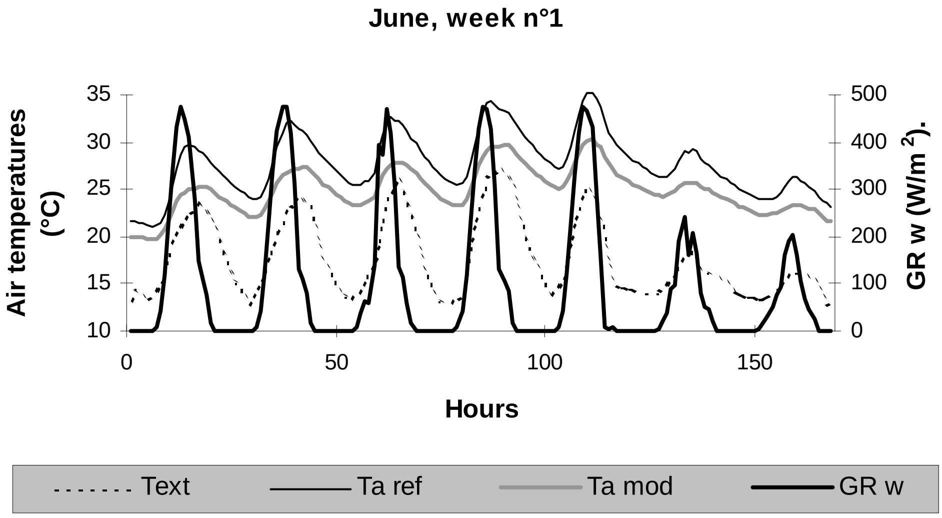

Fig. 9: Effect of the modification of the transparency of the window (from visual comfort criteria) on the indoor air temperature. GR w is the vertical global radiation on the window.

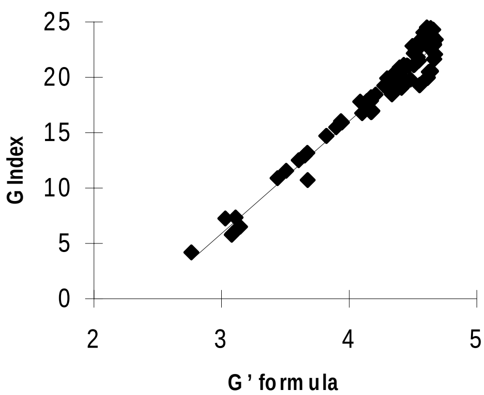

Fig. 10: Evaluation of Cornell glare index (G) from secondary parameters used in G' formula

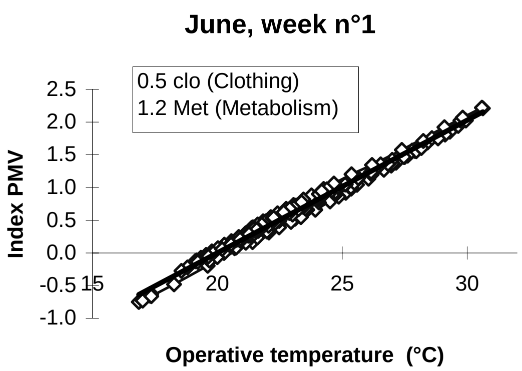

Fig. 11: Evaluation of PMV from operative temperature