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Energy and Buildings 28 (1998) 79-99

1998

Reprinted from

ENERGY AND BUILDINGS

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Received 15 October 1992; received in revised form 23 November 1997; accepted 27 November 1997

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Abstract

The system presented here, called Anidolic Ceiling, was developed to show the viability of intensive use of daylight by overcast outdoor conditions in nonresidential buildings. This device consists of a light-duct that is integrated in a suspended ceiling and leads midway into the office. Anidolic (nonimaging optics) elements are placed on either end of the duct, on the outside to collect light rays from the sky and on the inside to control the direction of the emitted light. The present paper describes the system design, as well as an experimental assessment of its daylighting performance in a comparison of a prototype and a full-size conventional facade, for a 6.6-m deep room. Measurements by overcast sky have established that the daylight factor on the work plane 5 m from the window is more than doubled. In addition, a monitoring campaign has shown that 30% of the energy for lighting can be saved. The system was also assessed with regard to the user. Visual comfort measurements (Laboratoire d'Ergonomie de la Vision's (LEV) method) were carried out showing that for both clear and overcast outdoor conditions, the visual environment quality is objectively improved at the rear working place. Furthermore, 33 people tested both rooms one after the other. They were submitted to a series of visual acuity tests on printed paper and on a computer screen and had to fill in a questionnaire. A comparative study showed that the personal appreciation of the luminous environment is better in the room with an Anidolic Ceiling, with a significant reduction of reading errors both on paper and on the screen.

Keywords: Daylight; Nonimaging optics; Anidolic; Light-duct; Visual comfort; Visual acuity tests

1. Introduction

This work was carried out in conjunction with an international program on daylighting in building, the aims of which are energy conservation and sustainable development in architecture. The goal of this study is the development of a system that increases the lateral penetration of daylight and improves the visual comfort in day-lit indoor spaces. It addresses the performance of a light-duct, designed for overcast sky conditions; it is thus concerned with nontracking methods and investigates the use of skylight as well as sunlight.

The light-duct is integrated in a suspended ceiling and leads midway into the room (cf. Fig. 1). The innovative feature is the use of nonimaging optics at either end of the duct, on the outside to collect light rays from the sky and on the inside to control the direction of the emitted light. Nonimaging optics has already proved to be very efficient in similar tasks, considering that image distortion is not a restriction [1,2]. To clearly mark the use of this theoretical framework, the system is called 'Anidolic Ceiling' ('anidolic' is a synonym of 'nonimaging' in ancient Greek [3]).

The present paper first describes some elements necessary for the design of anidolic components for a light-duct of rectangular section, focusing on numerical simulation results. Next, an experimental assessment is reported: it covers daylighting performances in terms of illuminance and energy saving as well as human response items such as visual comfort, visual acuity and acceptance. This study also yields some observations on differences between the effects of artificial and natural light.

2. Design considerations

2.1. Principles

2.1.1. General considerations

The main limitation to the use of a light-duct for daylighting by overcast outdoor conditions resides in its bounding section, because of the cost of adding a large volume to the building dimensions. Light concentration is essential to achieve adequate performances of the overall device, even

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PII S0378-7788(97)00066-2

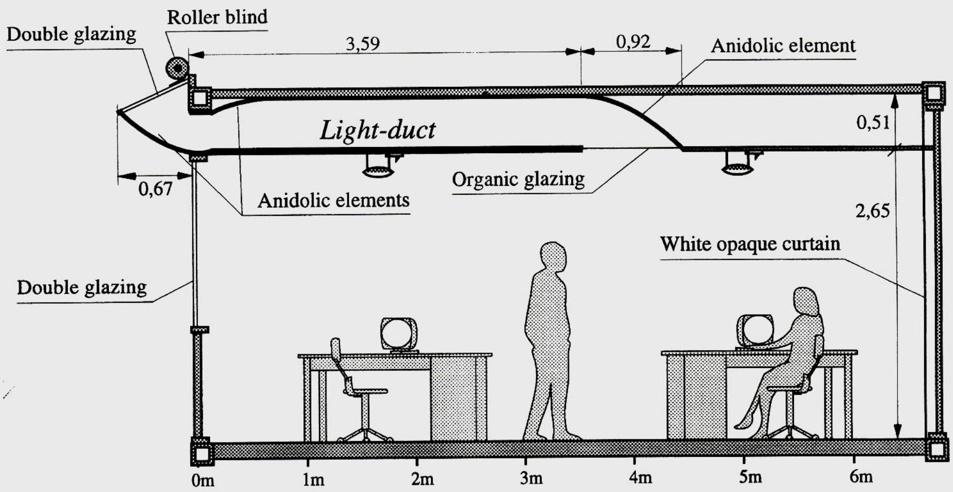


Fig. 1. The cross-section of the test room, fitted with an Anidolic Ceiling.

if the diffuse nature of daylight in the case of an overcast sky limits considerably the possibility of concentration (Lagrange Invariant Law) [4,5]. Going above this limit should theoretically be possible thanks to fluorescent material. This technology, however, is not yet applicable; research is under way to increase the fluorescence efficiency and photostability of the dye/matrix combination [6]. As a consequence, a concentration factor higher than the one obtained when the collector admission sector fits the brightest zone visible from the facade does not increase the light flux density in the duct; for a usual situation, it allows a factor around 2. On the other hand, using a refractive medium, like glass for example ($n \approx 1.5$), would allow, in the best case (a three-dimensional ideal concentrator), to increase the concentration factor proportionally to the square of the refractive index. Nevertheless, considering that typical values of the luminance of the skylight are around 4000 cd (candela) m^{-2} for an overcast sky, it is meaningless to reduce the light-duct thickness to under 1 decametre; filling the duct with a refractive medium seems therefore not applicable.

2.1.2. The anidolic ceiling

The present light-duct has a rectangular section: the reflective surface can be generated by moving a profile along a horizontal axis parallel to the facade; lateral ends are closed by flat reflectors. The collector is a two-dimensional, nonsymmetrical Compound Parabolic Concentrator (CPC, Fig. 2). It was used for the two following reasons:

(a) Its angular selectivity defines an admission sector of sharp edges: all the rays coming from the admission sector are transmitted, all others are rejected backward. Putting such an element at the entrance of the duct enables feeding it with sky rays only, as opposed to vertical window panes that let through as many rays coming from the sky as from the ground. By overcast sky, the brightness ratio between those two incidences is commonly around 5.

(b) Each admitted ray does not need more than one reflection to go through the concentrator; loses due to absorption in the collector reflectors are thus very weak.

The design of the collecting CPC consists in matching the admission sector on the visible part of the sky, from the horizon to the zenith. On the highest bound, however, a girder placed under the slab edge (usual feature in building structures), obstructs the light rays. In order to avoid this shadowing effect, the anidolic device is adapted using the method of 'variable extreme direction' [7]: the admittance angle varies along the entrance aperture from 90° (external edge) to 55° (internal edge), as illustrated in Fig. 3.

Two significant advantages are gained: (a) The width of the jutting part is reduced, allowing easier integration of the system in the facade. (b) In the case of multi-storey buildings, the sky obstruction due to a similar element placed on the floor above does no longer influence in a negative way the performance of the collector (upper collector out of the admission sector of the internal edge).

A flat element is placed on the upper part of the collecting anidolic component for the sake of simplicity. All other anidolic components are designed with a 'constant admission' sector: the exit part of the light-duct has a 90° angle admission

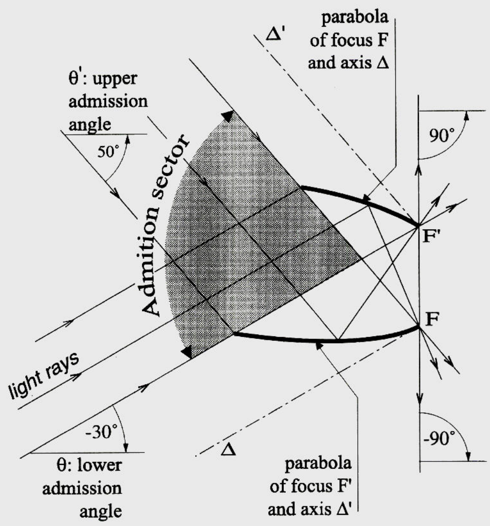


Fig. 2. The principle of a Compound Parabolic Concentrator (CPC).

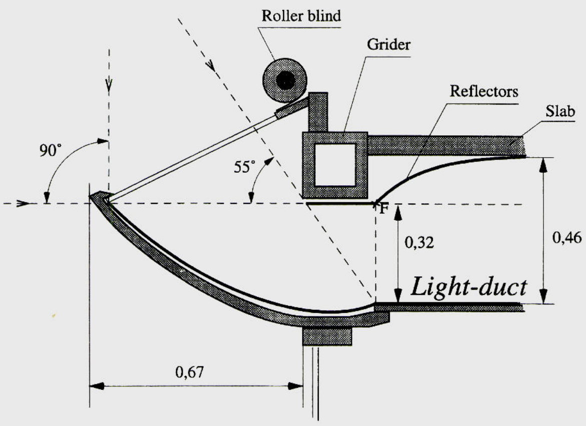


Fig. 3. The cross-section of the collector.

sector, which means that no light ray can be reflected back into the duct.

The resulting optic is scaled so that the light-duct takes up almost 0.5 m in height. In this figure, application is possible as the spacing from floor to slab reaches at least 3 m, which is the case for a lot of buildings of the 1950s/1960s, that are now to be refurbished.

2.2. Materials and their environmental impact

All the surfaces of the Anidolic Ceiling were covered with highly reflective optical material generally used for luminaries, including the straight part of the duct. This material is made of anodised aluminum foil (0.5 mm thickness), which is characterised by a very high regular reflectance ($\rho_r = 0.9$).

The use of aluminum foil leads to a nonnegligible amount of embodied energy (100 MJ m^{-2} in the case of recycled aluminum, 360 MJ/m^{-2} in the case of primary aluminum [8]). Industrial production of this daylighting device will therefore probably have to rely on aluminum depositing, which requires far less production energy (thickness of a few ten of micrometres).

The collector is covered with insulated double-glazing (regular transmittance: $\tau_r = 0.81$) at the entrance aperture for thermal reasons (cf. Fig. 1). A single panel made of organic material (plastic element) is placed at the exit aperture for safety and maintenance purposes (regular transmittance: $\tau_r = 0.9$). The entrance pane has a tilt angle of 25°, which is favourable for light rays from the upper sky dome and has the added advantage that rainfall can rinse off accumulated dirt.

2.3. Numerical simulations

2.3.1. Methodology

First validations have been achieved through numerical simulations. A test room equipped with an Anidolic Ceiling is compared to an identical one fitted with double-glazing (reference facade), ensuring cloth thermal isolation. To make this comparison relevant also regarding the volumetric aspects of design in architecture, the total fraction of the facade plane through which the light propagates is the same in both cases.

The two cells mock up conventional office rooms: the indoor surfaces are achromatic and painted white (walls, ceiling) or grey (floor carpet). To allow a sound comparison of daylighting performances, they have strictly identical geometrical and photometrical indoor features:

Internal dimensions	3.05 m (l) × 6.55 m (d) × 3.05 m (h)
Surface reflection coefficients:	0.80
Walls	
Ceiling	0.80
Frames	0.81
Floor	0.15
Outdoor ground	0.20
Glazed facade: Glazing ratio	0.26
Window transmittance (at normal incidence)	0.81

Horizontal illuminance is calculated at 7 points that are regularly spaced along a central longitudinal line and placed at desk height (0.75 m above the floor). The light propagation was simulated with the software Radiance [9]; this calculation tool is based on backward stochastic adaptive ray tracing. It takes into account refraction and reflection at each interface. The present investigation is limited to visible wavelength. Calculation of an illuminance profile in the room fitted with the Anidolic Ceiling takes around 4 h on a work-station (Sun Sparc 20). This is eight times longer than in the reference case, a difference that is due to the high number of reflections that occur inside the duct. This is all the more true as the computer model of the test case takes more memory space since each curved reflectors have to be split into plane quadrilaterals (50 per anidolic component in the present case).

The software Radiance has been validated several times [10] and, in the present study, the uncertainty of the outputs is estimated by comparison with measurements (cf. Section 4.1).

2.3.2. Daylight factor profile

The sky is assumed to be overcast; at first approach, the skylight luminance is distributed according to the CIE model [11]. Daylight factor profiles calculated in both rooms are given in Fig. 4, showing an obvious enhancement at the back of the test room due to the Anidolic Ceiling. The average daylight factor (D_{rear}), calculated for the four deepest points in both rooms (3.7 m to 6.4 m from the window), is multiplied by a factor 2.0. It means that the Anidolic Ceiling, even if it takes only 1/5 of the facade's glazing area, brings practically as much light as the overall glazed area to the back part of the room.

Besides, a decrease in the daylight factor close to the window (from 18% to 14%) is obtained through an overhang effect, which softens the illuminance level in a part where there is usually too much light. The illuminance uniformity ratio (= minimum/average, CIE definition [12]) goes from

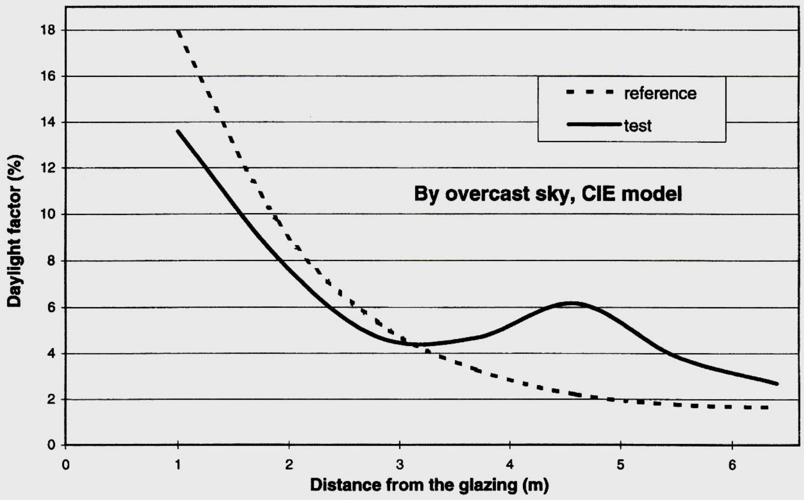


Fig. 4. Comparison of simulated daylight factors profiles in the test room (Anidolic Ceiling) and the reference room (double glazing facade).

Table 1
The characteristics of the daylight penetrations, for three models of overcast sky

Overcast sky model	D_{rear}: mean daylight factor (from 3.7 to 6.4 m)			Uniformity ratio (standard deviation to average, from 1 to 6.4 m)	
	Test	Reference	χ: test/reference	Test	Reference
Isotrope	5.0	2.9	1.7	0.54	0.84
CIE	4.4	2.2	2.0	0.54	0.92
CIE with 40° obstruction (urban)	3.4	1.2	2.8	0.53	1.11

0.3 in the reference case to 0.4 in the test case. This does not produce a significant change because the increase of the minimum is balanced by the increase of the average. Now, considering instead the ratio of the standard deviation to the average shows that the Anidolic Ceiling improves significantly the illuminance uniformity (ratio of 0.54 as compared to 0.92 in the reference room). Table 1 summarises these characteristics together with those obtained for two other overcast sky models: isotropic sky, and CIE distribution with an obstruction of 40° above the horizon, which corresponds to an urban environment.

The enhancement of the daylight level in the rear room is a little weaker with the isotropic sky than with the CIE model (1.7 instead of 2.0); this effect is naturally due to the fact that the contribution of the facing lower part of the sky dome does not need to be deflected to reach the bottom of the room. On the other hand, in urban surroundings, the obstruction increases significantly the benefit of the Anidolic Ceiling; the enhancement ratio goes up to 2.8. In addition to those improvements, Table 1 shows also that the uniformity of the daylight penetration in the test room is only weakly dependant on the sky luminance distribution, as opposed to the reference case.

2.3.3. Light efficiency

The light flux through the device was calculated by integration of the luminance over the duct section. Fig. 5 illustrates the values of the flux at different cross planes of the duct, obtained for a CIE overcast sky with up to 10,000 lux on the horizontal plane and no obstruction. To take into account the obstruction constituted by the facade and the upper collector on the flux available at the entrance aperture, the facade is assumed infinitely larger than the room cross-section (uniform boundary condition) and its reflectance is set to 0.2.

Making the ratio of the emerging and incoming light fluxes for different parts of the anidolic duct gives the following optical efficiency values.

Double glazing, at entrance aperture	78%
Anidolic collector	72%
Light duct, excluding the collector	68%
Simple glazing, at exit aperture	84%

The efficiency of the whole anidolic system, including glazing, is 32%.

It is interesting to note that double-glazing ($\tau_r = 0.81$) is less penalised than simple glazing ($\tau_r = 0.90$), probably because the incidence of the brightest rays are more favourable for the first. Another striking feature is that, although the collector takes only less than 1/6 of the duct length, its efficiency (72%) is relatively close to the one of the rest of the duct (68%); this feature is due to the fact that the sky zone partially cut off by the variation of the collector admission angle is the brightest in the overcast CIE sky model [11].

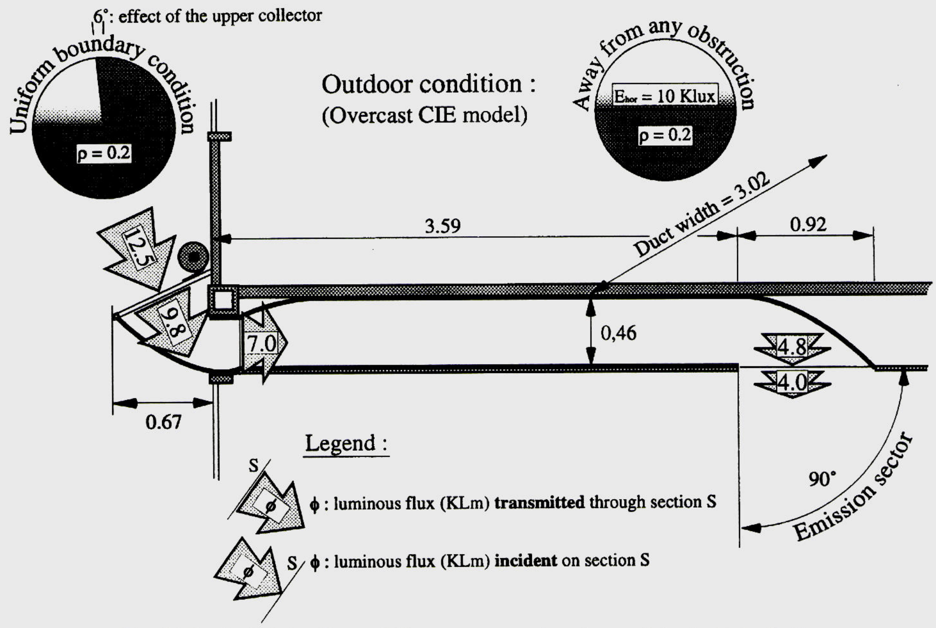


Fig. 5. The daylighting flux at different cross-section planes of the Anidolic Ceiling.

This is, however, better than collecting rays that are shaded by the girder placed under the ceiling slab (cf. Section 2.1). An alternative would consist in shifting outward the collector until its focus point is positioned at the external edge of the girder. At the same jutting width, this would nevertheless imply scaling down the collector, and consequently, reducing the transmitted flux.

2.3.4. Bibliographic comparison

Bouchet and Fontoynont [13] give an expression of the efficiency of vertical light-wells under a CIE overcast sky. This study was carried out with 'Genelux', a computer program that is different from the one used in the present work, which makes the comparison more valuable. They have investigated specular ducts of rectangular sections with shape ratio from 1 to 5; extrapolation to the present case (value of 6.57) seems reasonable. Considering only the straight part of the Anidolic Ceiling (2.91 m long), their formula gives an efficiency of 61%; our simulation gives 72%. The observed difference could be expected since the luminance distribution at the entry aperture is not the same: the two anidolic admission components reduce the portion of the flux transmitted by rays coming with a high incidence angle, which in turn reduces the losses by absorption. Both simulations are, therefore, in good agreement.

2.3.5. Impact of anidolic components

To assess the impact of the anidolic components, together with the reflectivity of the system's surfaces, the following computer simulations were carried out: (a) The regular reflection coefficient (ρ_r) of the system surfaces was reduced from 0.9 to 0.8 (the shape of the anidolic elements was kept unchanged); (b) All the curved parts of the system were replaced by flat surfaces (ρ_r was kept unchanged).

It appears that both modifications have a significant impact on daylighting performance (cf. Fig. 6). The following conclusions can be drawn from this analysis: (a) The use of flat surfaces instead of anidolic components reduces the overall system efficiency by 50%; (b) A lower reflectivity of the Anidolic Ceiling surfaces (0.8 instead of 0.9) reduces the same efficiency by 45%.

As a consequence of this analysis, particular attention was paid to carefully producing and mounting the different components of the Anidolic Ceiling.

3. Prototype and monitoring equipment

Two mock offices were constructed to the same dimensions, and painted and carpeted with the same materials. Their geometrical and photometrical characteristics are those of the models used for the numerical simulations (cf. Section 2.3). The two modules face the same direction. Both were placed on the same circular platform in order to guarantee strictly identical outdoor daylighting conditions. The modules stand side by side and are mounted on rollers: consequently they can be oriented in any direction. There are no physical obstructions around them at an altitude higher than 10° above the horizon.

A prototype of an Anidolic Ceiling was installed in the test room. The facade is prefabricated in metal, white painted steel for the frame and aluminum layout for the collector (Fig. 7a). All the external parts of the system are thermally insulated to avoid thermal bridges and water condensation (7 cm of glass wool). To curve the reflectors, they were glued onto a profiled wooden structure. At delivery, a plastic film protected the aluminium foils; it was, therefore, possible to work without causing damage till this protection was

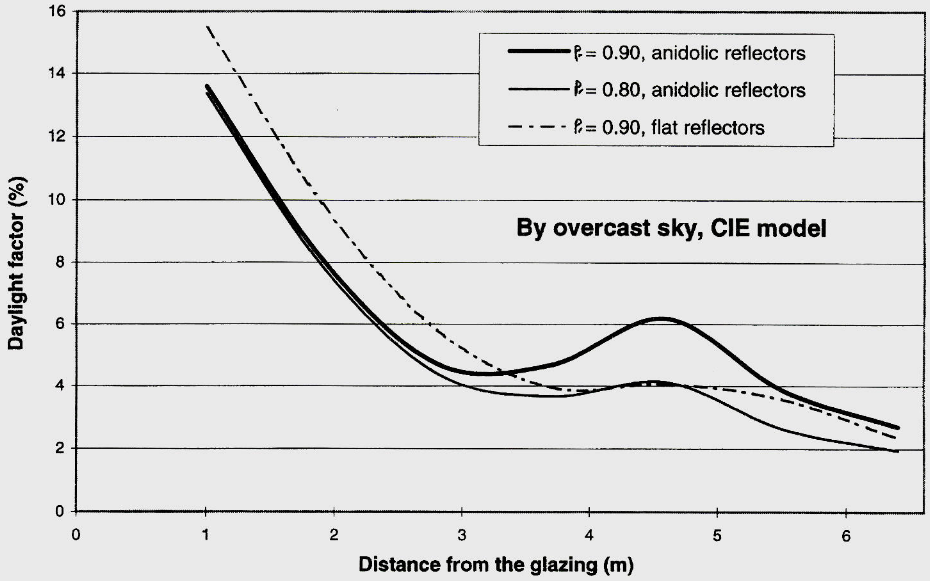


Fig. 6. The impact of anidolic components and surface reflectivity on the daylighting system performance.

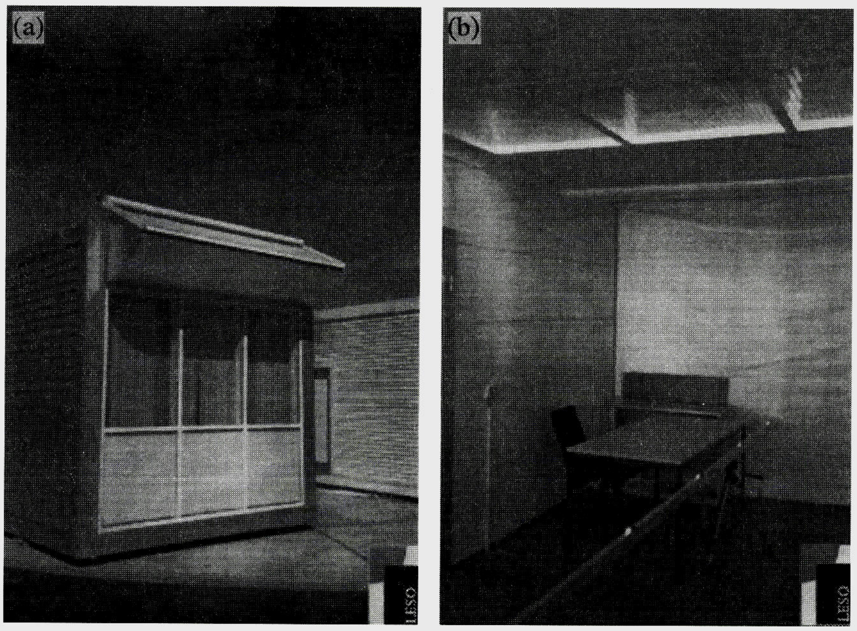


Fig. 7. (a) The front view of the test room. (b) View of the rear of the test room.

removed just before closing the ceiling. This technique was found to be well adapted for a single prototype; it is however certainly not the most cost-effective for series.

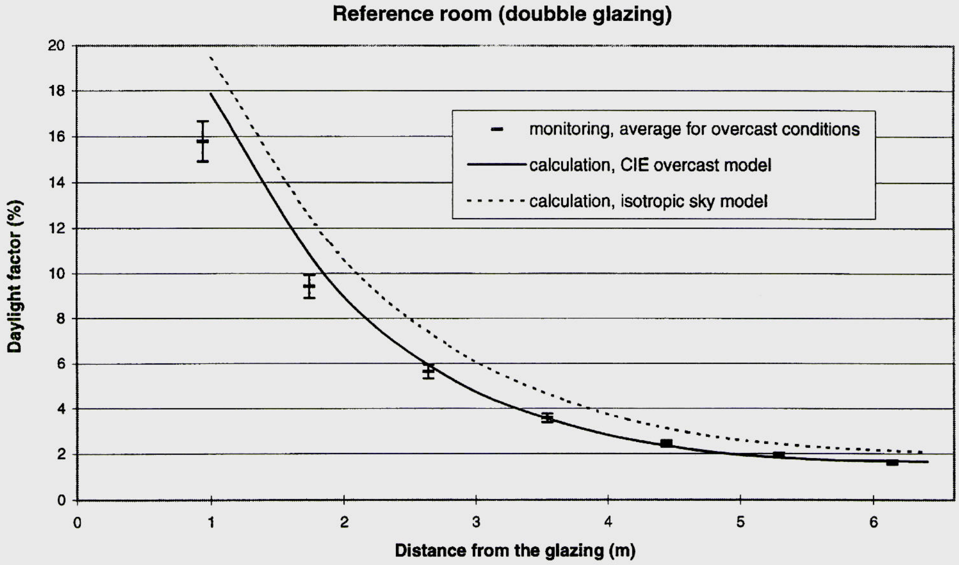
Indoor illuminance measurements were done with two sets of seven sensors: they were fixed at regular distances on a horizontal girder placed at desk height (0.75 m). All sensors were calibrated before the monitoring campaign, leading to an accuracy estimation better than $\pm 3.5\%$ on average. Fig. 7b gives a view of the indoor illuminance sensors' configuration. A 'sensor head', placed on the roof of a module, was used to assess the daylighting availability; 5 illuminance-meters are measuring the following data: (a) the horizontal global illuminance (E_{ext}), and (b) the vertical global illuminance on the four different planes of the facades.

All sensors are waterproof and fitted with a temperature drifting correction circuit: their accuracy is estimated better than $\pm 2.5\%$ for the horizontal sensor and $\pm 3\%$ for the vertical ones. They are fixed on a platform painted in black and made of honeycomb steel to avoid parasitic reflections.

4. Daylight factor measurement

4.1. Performance under overcast sky

Both modules were oriented due north to assess the daylighting performance of the Anidolic Ceiling under overcast sky (more stable and uniform luminance distribution). A first



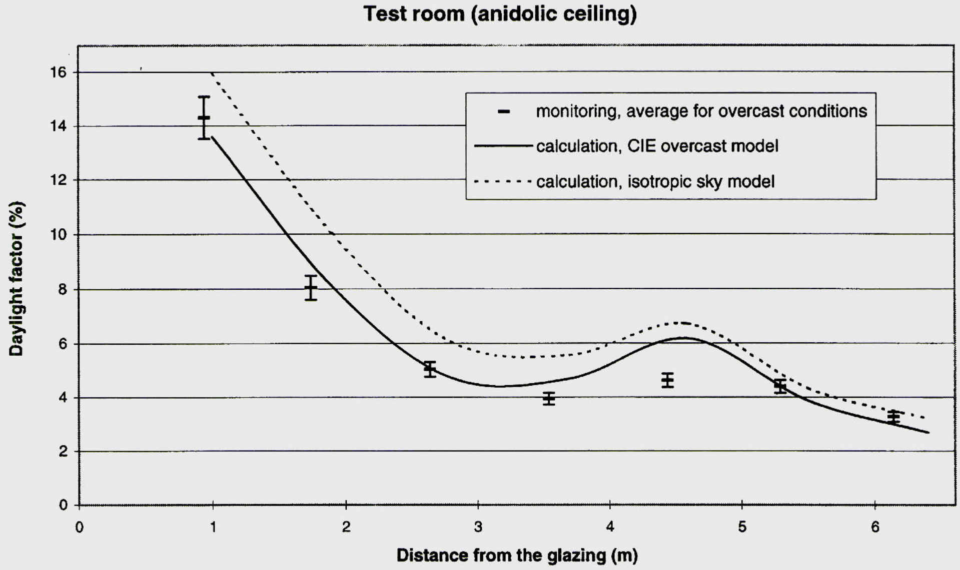


Fig. 8. Comparison of monitored and calculated daylight factor profiles in the test room (Anidolic Ceiling) and the reference room (double glazing facade).

set of 43 data acquisition operations was carried out at variable time intervals during a period of 40 min: visual observation was used to check the persistence of overcast sky conditions during the whole period.

In order to obtain sounder and more reproducible data of the daylighting conditions, a Sky Asymmetry Index (SAI) equal to the ratio of the standard deviation (σ) of the four external vertical illuminance values to their average ($\bar{E}$) was proposed (instantaneous values). The following equation gives the mathematical definition of this index:

$$\mathrm{SAI} = \frac{\sigma(E)}{\bar{E}} = \frac{1}{2} \cdot \sqrt{\sum_{i=1}^{i=4} \left(\frac{E_i}{\bar{E}} - 1 \right)^2}$$

where: E_i is the external vertical global illuminance, i varies from 1 to 4, one item per plane of the four sides.

This indicator shows a high sensitivity to the sky luminance distribution in the case of cloudy skies. Measurements over days of changing weather conditions led to considering a fully clouded sky vault for SAI values lower than 10%, as overcast skies show a higher symmetry.

Fig. 8 shows the daylight factor profiles monitored in both rooms after averaging of the monitored data. The comparison of the monitored and calculated profiles shows good agreement for the two rooms, assuming a CIE standard overcast model for the computer simulations. For the reference room (double-glazing facade), the difference between the two different profiles is even lower than 1% for positions close to the window (about 1 m from the facade), although modelling of the window frame brings about some inaccuracy here.

For the test room (Anidolic Ceiling), the monitoring confirmed the performance assessment through simulations; the calculated profile fitted well within the error bars of the measurements for a majority of points. Nevertheless, this is not the case with the values corresponding to the points that lie directly under the light duct aperture, which show significant discrepancies that reach up to 20% (4.9% monitored instead of 6.2%). The average daylight factors at the rear part of the room (D_{rear}) correspond, however, reasonably well (4.0% monitored instead of 4.4%): a close multiplication factor of D_{rear} is observed due to the Anidolic Ceiling (value of 1.7).

There are explanations for the observed discrepancy between the two curves: (a) inaccuracies during the construction of the modules' structure (estimated at ± 2 cm) penalized the positioning of the anidolic daylighting collector during its set-up (cf. Fig. 1); (b) irregularities of the system's reflective surfaces (thermal strains, gluing problems, etc.) decrease the efficiency of the Anidolic Ceiling compared to the theoretical values.

The monitored data confirm, however, the outstanding daylighting factors in the rear of the room.

Placing a hollow acrylic plate on the exit aperture of the light duct even further improved the daylight distribution in the room, making the perceived luminance on the walls smoother and blurring the vision through the duct. Measurements have shown that the daylight factor profile is kept almost unchanged when this element is placed instead of the regular glazing (the absolute difference stays below 0.6%); it was therefore left in this position during the rest of the experimentation.

4.2. Performance under clear sky

4.2.1. With sunshine on the facade

The daylighting modules were oriented in a different direction for the assessment in sunny conditions:

- to the south, to investigate the effect of sunlight penetration through the facade;
- to the north, to investigate the opposite case (absence of solar penetration).

Fig. 9a–d shows comparisons of daylight illuminance profiles in both monitoring modules under clear skies in absence of any solar protection on the anidolic collector. Four sun positions were monitored: for each of the summer and winter situations (high and low solar stroke), two azimuths relative to the facade are considered, facing and skewed sunshine.

The different behaviours are directly linked to the sun position relative to the facade. It can be seen that: (a) a multiplication of the daylight factor, reaching the value of 12, is observed at 5.3 m from the window for a high solar position (65°) and a normal sun position on the facade (cf. Fig. 9a); (b) the illumination at the bottom of the room is generally uneven (cf. Fig. 9a,c,d); (c) for low incidence angles of sunlight on the facade (cf. Fig. 9d), both profiles are similar.

The very high measured illuminance values confirm the necessity of equipping the anidolic collector with external solar protection. Two different solar protection systems were installed on the test room facade:

- a curtain of vertical mobile slats in off-white fabric was hung up in front of the window;
- an opaque fabric blind was installed in front of the anidolic collector glazing.

Closing of these solar protection blinds led to more reasonable values in the test room: typically one Klux in summer

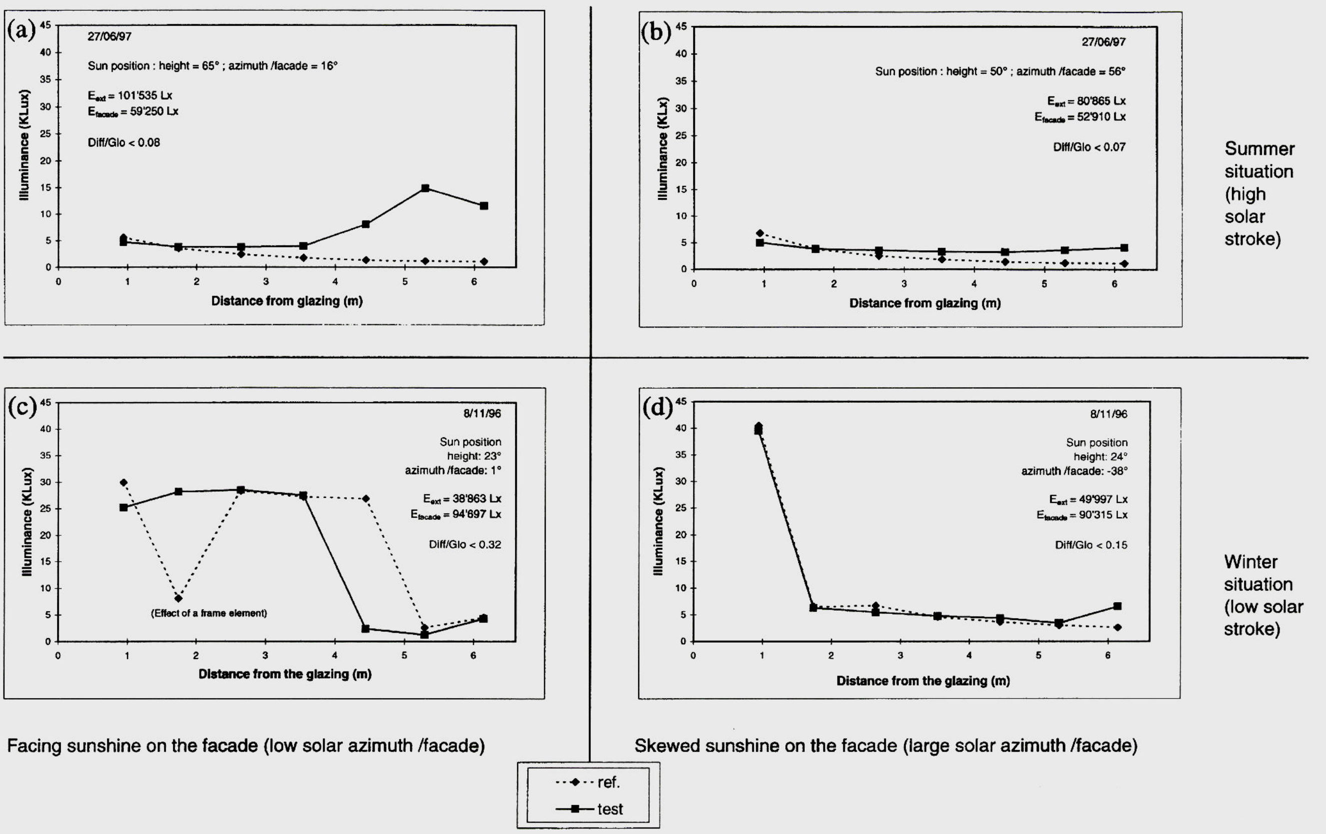


Fig. 9. The monitored daylighting illuminance profiles in both rooms in absence of any solar protection.

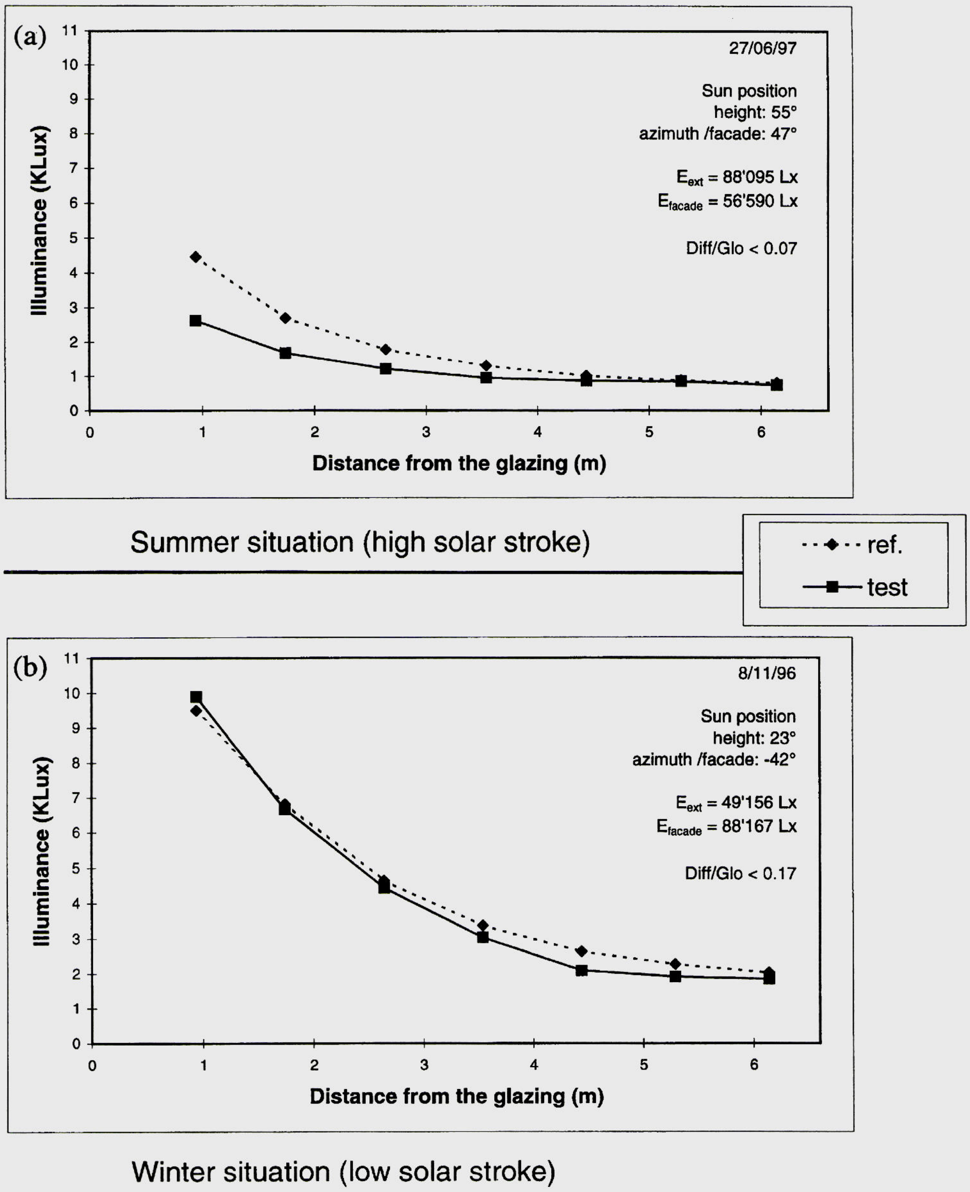


Fig. 10. The monitored daylighting illuminance profiles in both rooms in the presence of solar protection (fabric blinds rolled down over the anidolic collector, curtain closed in both rooms).

(cf. Fig. 10a) and three Klux in winter (cf. Fig. 10b), for skewed sunshine (45° azimuth angle on the facade).

These illuminance levels remain relatively high for computer office desks; in the case of a real building, the view window should be fitted up with an external venetian blind, which is also more appropriate with regard to thermal comfort.

When there is no sunshine on the facade (modules oriented to the north), measurements show that the penetration of daylight is similar in both rooms (cf. Fig. 11); in particular, the level of illuminance reached at the rear of both rooms is equal. This indicates that the light flux due to the Anidolic Ceiling offsets the shading effect of its overhang.

The data monitored during sunny conditions confirm the efficiency of the Anidolic Ceiling in redirecting daylight to the back part of an office room. The integration of solar protection on the external anidolic collector is, however, a 'must' considering the high light flux emerging from the system when the facade is in full sunshine.

5. Lighting energy performance

Although energy savings from room heating can obviously be expected from an Anidolic Ceiling thanks to the additional solar gains obtained from the daylighting system in winter, energy monitoring was deliberately limited to the assessment of energy savings from lighting. Most of the artificial lighting is used in office buildings at daytime under overcast outdoor conditions. In countries of temperate climate, and this is the

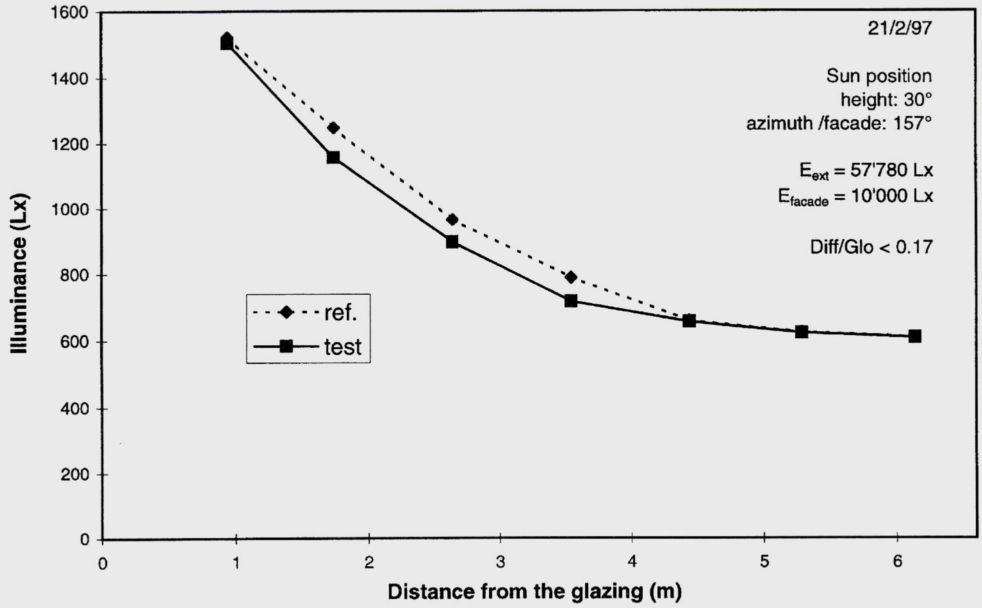


Fig. 11. The monitored daylight illuminance profiles in both rooms in sunny conditions and in absence of any sunshine on the facade (northern orientation).

case of the region of Switzerland where this experiment took place, this kind of sky occurs frequently, particularly in winter and mid-season.

5.1. Monitoring

The energy performance with regard to lighting (savings due to the Anidolic Ceiling) in practice strongly depends on user behaviour. Visual comfort imperatives usually drive the users' utilisation of louvers and blinds. An assessment of the system in the presence of users was, however, out of the scope of this particular project: the monitoring of energy performance was therefore carried out in the 'optimal conditions' corresponding to empty office rooms.

The two daylighting modules were oriented due north for this experiment in order to avoid interference from blind management. It is assumed that a northern orientation offers stable and adequate visual comfort conditions even without the use of blinds.

Both modules were fitted up with the same electrical appliances: two rows of recessed luminaries, located at the first and the third fourth of the room length and at the same height in both rooms (cf. Fig. 1). Each luminary is equipped with two 36-W fluorescent tubes, driven by electronic ballast. A daylight responsive controller allows dimming of each of them through a photo sensor that is fixed to the ceiling behind the luminaries, their input beam being collimated toward the back of the room. The work plane illuminance was set at 300 lux ($\pm$15%) on each desk; it was checked regularly through nighttime measurements. Work hours start at 0800 and finish at 1830 (legal time). Lighting electricity consumption was measured in both modules with wattmetres that deliver an impulse every 1 W h (accuracy $< \pm 1.5\%$).

A total of 24 half-day measurements spread over 14 weeks from February through June were taken into account (cf. Fig. 12). Illuminance and energy related data were simultaneously monitored during these periods with a 10-min time step. A comparison of the overall lighting electricity consumption of the two modules shows total savings of 31%. The following absolute figures were measured during this period:

Lighting consumption of test room	1.949 kW h
Lighting consumption of reference room	2.828 kW h

These monitoring results stand in good agreement with the savings figures calculated according to the Swiss recommendation for daylighting [14]: yearly lighting savings of 30% are predicted by this method which allows the statistical calculation of the daylighting autonomy of an office room for a given nominal desk illuminance (300 lux in this case) on the basis of the daylighting factor.

Electricity savings of a third of the consumption for lighting can reasonably be expected from an Anidolic Ceiling in a conventional 6.6 m deep office room. When compared to a normal double-glazing facade, these savings are achieved at the back of the room, where the second desk is placed (5 m from the window). It must be emphasised, however, that this result assumes daylight responsive dimming control of the electric lighting, independent of user behaviour. The control of solar blinds as well as lighting by users can lead to totally different figures, depending on user consciousness regarding energy savings.

5.2. Impact of meteorological conditions

As the savings due to the Anidolic Ceiling depend on the sky luminance distribution, an analysis of the influence of the external daylighting conditions (sky cloudiness, outdoor illuminance) over lighting savings was carried out. The half-day

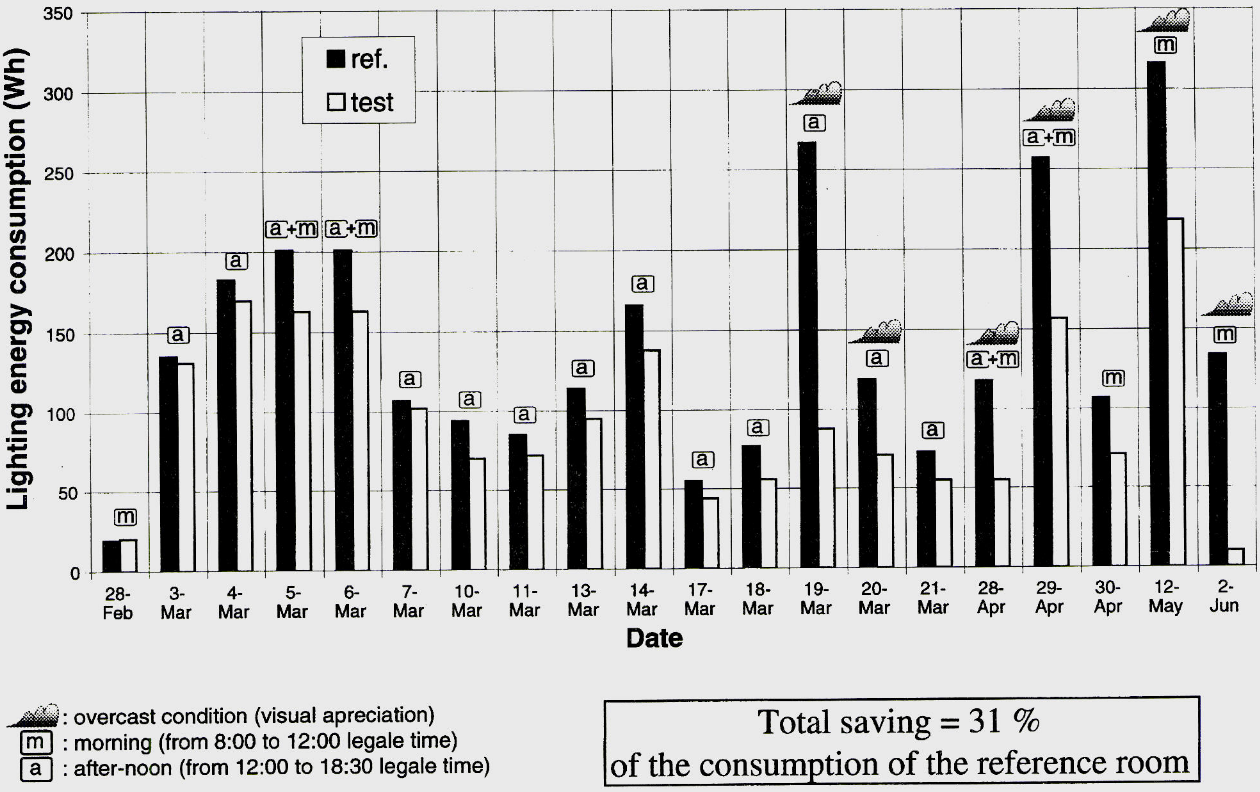


Fig. 12. Lighting energy consumption monitored in the two rooms during 24 half-days.

interval has been chosen to take advantage of the daylight periodicity.

Half-day saving fractions (SF_{hd}) and half-day sky asymmetry indexes (SAI_{hd}) were determined and plotted together in order to retrieve a possible relation between them. Fig. 13 illustrates the correlation between the two parameters obtained through monitoring. The hyperbolic correlation function gives the following equation:

$$SF_{hd}[\%]=\frac{1.1}{SAI_{hd}}$$

This relation shows that savings are much larger under overcast conditions (symmetrical sky) than when the sky is clear. By clear weather, let say if $SAI_{hd}>30\%$, the savings represent only 20% of the total obtained over all the monitored half-days, although this weather condition corresponds to 58%. This can be explained by the fact that, on clear days, the lights are off during almost the whole daylight period in both rooms, whereas, on overcast days, the difference in daylight factors at the rear desks brings about large differences in power and duration of electricity supply.

Fig. 14 shows, moreover, how the quantity of electricity savings depends on the relative value of the desk daylight illuminance ($E_{ext}\cdot D_{rear}$) to the required desk illuminance E_0. When the sky is overcast, three different situations can be distinguished regarding savings: (a) a first case where the desk daylight illuminance in both rooms is lower than the required illuminance ($E_{ext}\cdot D_{rearTest}<E_0$), leading to moderate savings (beginning and end of daytime); (b) a second case where only the desk daylight illuminance in the test room is higher than the required illuminance ($E_{ext}\cdot D_{rearTest}>E_0>E_{ext}\cdot D_{rearRef}$), which leads to high savings (intermediate periods); (c) a third case where both desk daylight illuminance values are higher than the required level ($E_{ext}\cdot D_{rearRef}>E_o$), which leads to the switching off of the lighting in both cases (no savings, summer days).

This variation is taken into account by correlating the saving fraction (SF_{hd}) and the outdoor horizontal illuminance ratio, defined as follows:

$$\varepsilon_{hd}=E_{hdExt}\cdot D_{rearRef}/E_0$$

where E_{hdext} is the half-day outside horizontal illumination, averaged only over the period of electric lighting; $E_0/D_{rearRef}$ is equal to the outside daylight level that must be reached to switch off the rear light in the reference room.

Linear regression of SF_{hd} vs. $1/SAI_{hd}$ and second order polynomial of ε_{hd} gives the following model:

$$SF_{hd}[\%]=\left(3.0+1.7/SAI_{hd}\right)\cdot\varepsilon_{hd}-\left(2.6+0.5/SAI_{hd}\right)\cdot\varepsilon_{hd}^2$$

This regression is forced to meet the origin for $\varepsilon_{hd}=0$ at any nonnull SAI_{hd} since no saving can be expected at nighttime. Fig. 15 shows the trace of this equation in three slices defined by $1/SAI_{hd}=k\pm2$ with $k=3$, 7 and 11, which allows a comparison with measurements (represented by dots) for skies of close symmetry. The fit seems satisfying since only one point lies apart; the standard error of the regression is below

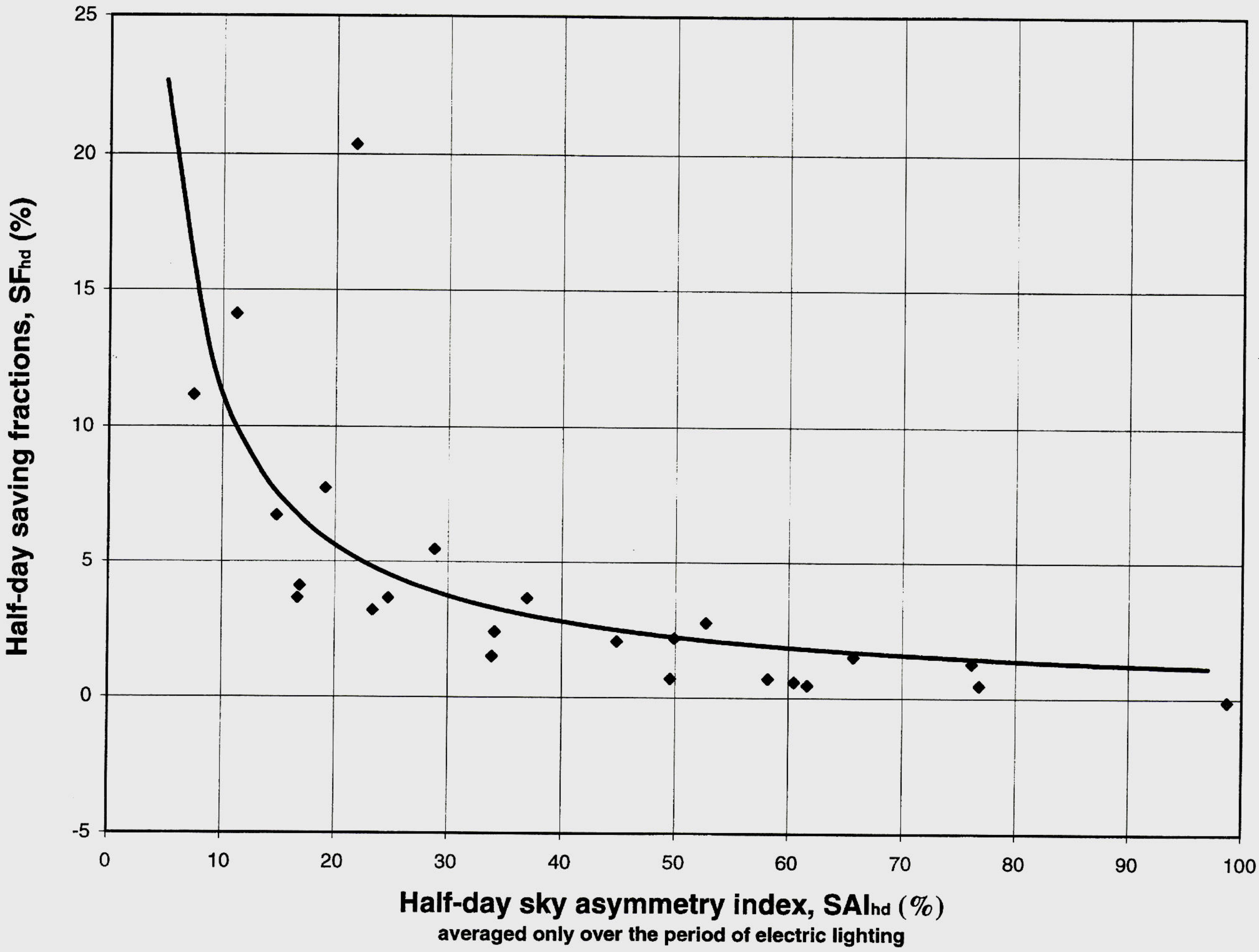


Fig. 13. The empirical correlation observed between the electricity savings fraction (SF_{hd}) and Sky Asymmetry Index (SAI_{hd}) averaged over half-day periods.

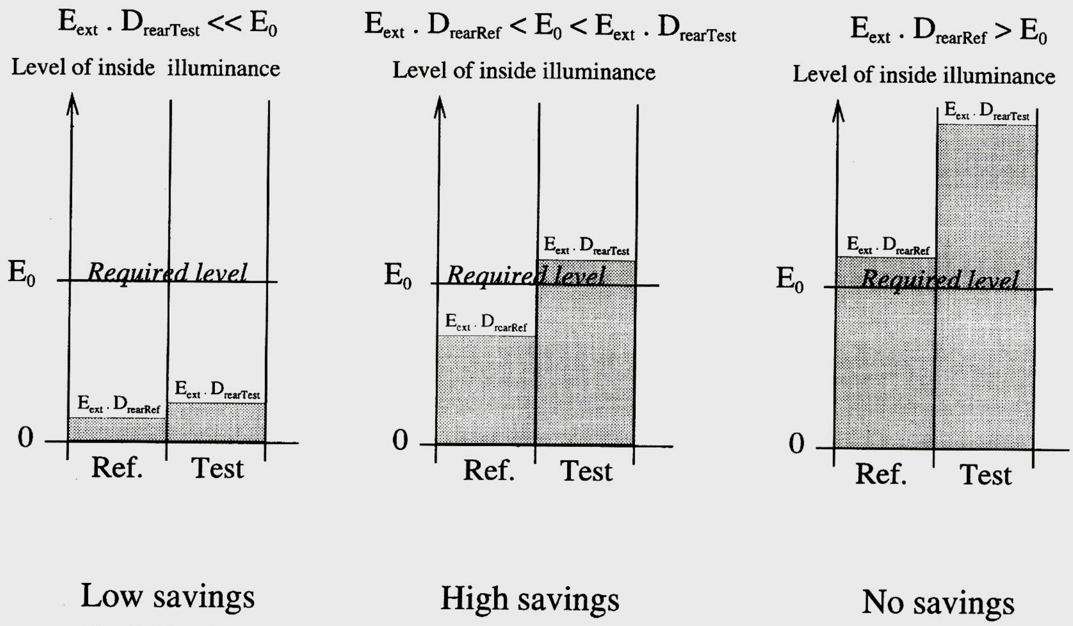


Fig. 14. The schematic behaviour of lighting savings as a function of the external daylight illuminance E_{ext}.

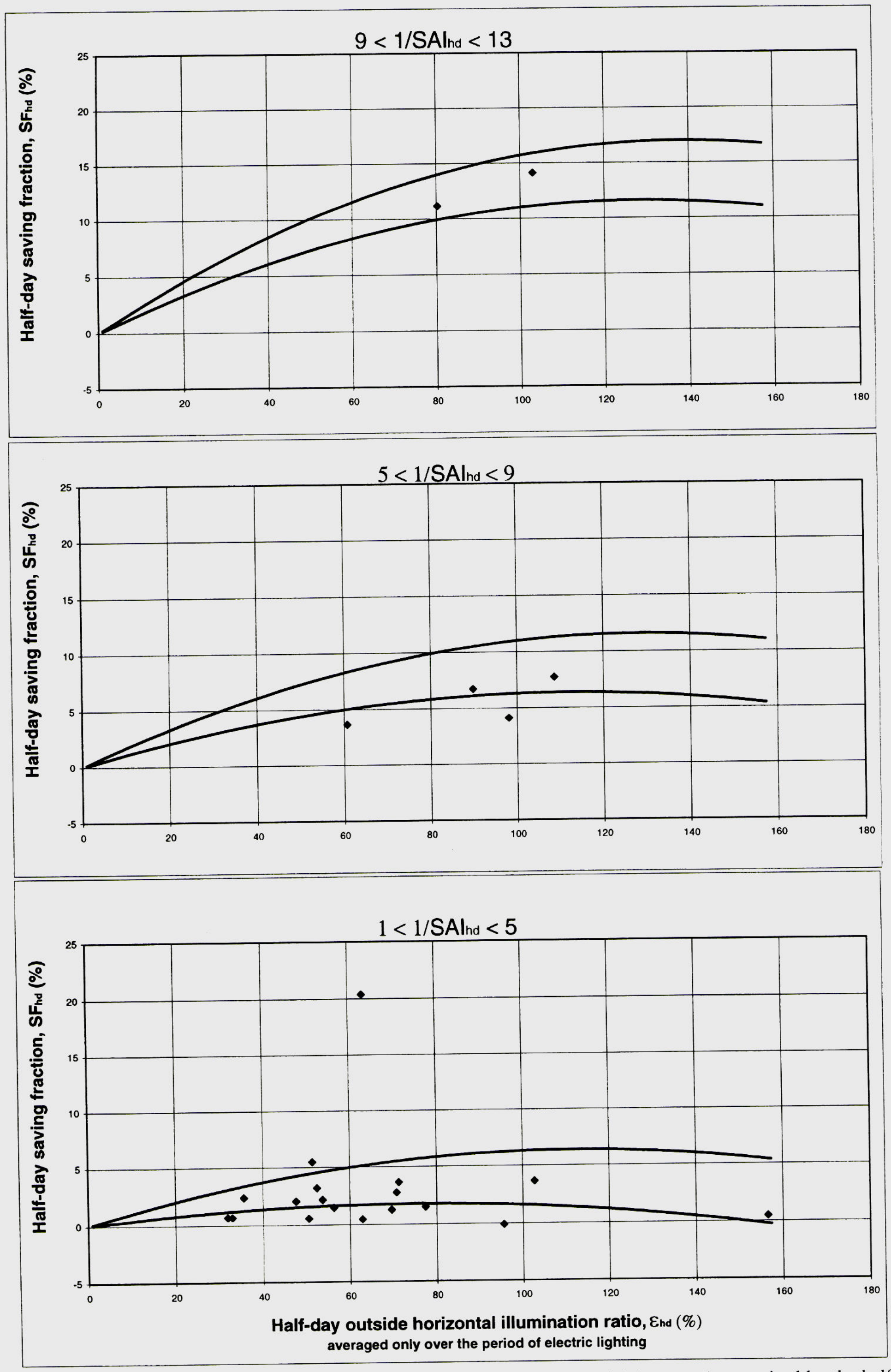


Fig. 15. The correlation between half-day fraction of total electricity saving (SF_{hd}) and the sky brightness, characterised by the half-day outside horizontal illuminance ratio (ε_{hd}).

3.9. In addition, this model is in good agreement with the mechanism illustrated above (cf. Fig. 14): the maximum abscise is around 100% and increases logically for overcast conditions. One may also note a few dots on the right of this limit; this is not in contradiction with the effect of the daylight responsive control because of its temporisation (daylighting must be continuously sufficient during 15 min), all the more so since the rear parts of the rooms are unlikely affected by

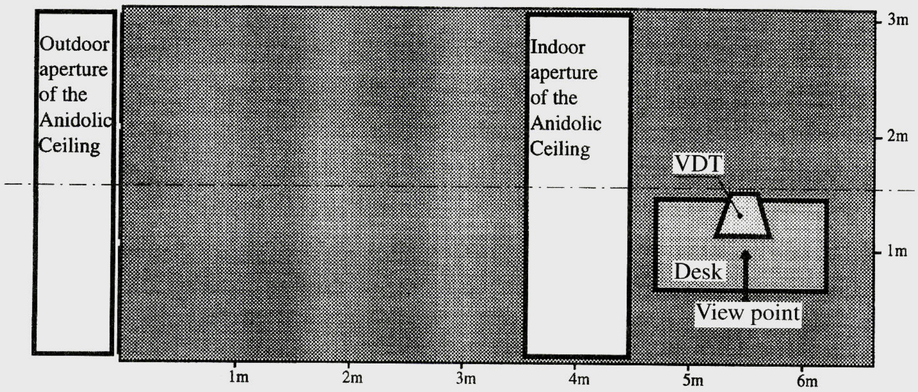


Fig. 16. Position of the work place analysed regarding luminous work environment.

sunny spells, the facades being north oriented. In this respect, the highest measured value of ε_m (157%) occurred logically by variable meteorological conditions.

6. Monitored luminous work environment

An evaluation of the quality of the luminous work environment in both modules with regard to daylighting was carried out within this project. The following procedure was used to assess the visual comfort and performance for that purpose:

- visual comfort conditions at the work desk were determined through luminance scanning,
- human response tests to lighting conditions were carried out on a group of subjects.

Both modules were oriented due south for that analysis; this orientation was chosen in order to take into account possible glare risks due to the direct sun penetration into the modules. Furniture, desks and video display terminals (VDT) were identically set in both rooms in order to allow an objective comparison of the luminous work environment in the two modules. The evaluation is focused on the working place of the rear of the rooms which, for the test cell, is 1 m behind the indoor aperture of the Anidolic Ceiling (cf. Fig. 16). The desk orientation was chosen following recommendations in ergonomics so that the main vision axis of the desk users is parallel to the window.

Table 2
Overcast sky, all blinds opened (external horizontal illuminance is normalised to 10 klux)

	Reference	Test
Mean luminance ratio (surrounding/VDT)	0.3	0.7
Mean luminance of the document (cd m^{-2})	27	65
Pupil illuminance (lux)	53	158
PPD for a printed document (%)	**40**	**32**
PPD at VDT (%)	**40**	**32**

6.1. Measurement of the visual comfort

The visual comfort was assessed with a methodology and monitoring equipment recently developed at the LEV (Laboratoire d'Ergonomie de la Vision) [15–17], which is based on a hemispherical scanning of the luminance seen at a workplace. The method assumes two kinds of user tasks:

- reading of a black/white printed document;
- reading of a VDT computer screen (100 cd m^{-2} average luminance).

The directional sampling is entered in a physiological mathematical model of visual acuity that gives a prediction of the Probable Percentage of Dissatisfied (PPD). A 38% PPD value is considered as an upper limit regarding visual comfort, as higher values express visual discomfort (glare). The upper limit usually considered as acceptable is 50%.

Tables 2 and 3 summarise the results, giving the PPD values assessed for overcast and clear sky conditions. By overcast sky (cf. Table 2), the additional daylighting brought through the Anidolic Ceiling improves the luminance ratio in the view field (ratio closer to unity) and reduces significantly the PPD values for paper as well as for VDT reading tasks, going beyond the comfort limit (38%).

The analysis of the situation under clear sky conditions (cf. Table 3) shows mixed results, depending on the presence

Table 3
Sunshine on the facade, internal fabric blinds closed, Anidolic Ceiling blind down and up

	Reference	Test	
		Anidolic Ceiling solar protection position	
		Down	Up
Mean luminance ratio (surrounding/VDT)	1.5	1.7	1.9
Mean luminance of the printed document (cd m^{-2})	244	163	311
Pupil illuminance (lux)	602	383	1021
PPD for a printed document (%)	**31**	**30**	**33**
PPD at VDT (%)	**56**	**44**	**86**

or absence of a solar protection in front of the anidolic collector: (a) when solar blinds are down, the PPD values for VDT tasks are lower for the Anidolic Ceiling, providing a better visual comfort; (b) when the solar protection is open, excessive PPD values (higher than 50%) are experienced for VDT tasks.

This set of results shows that the Anidolic Ceiling provides an adequate lighting work environment, even for extremely high illuminance values characterising sunny skies. The necessity to integrate solar protection in front of the anidolic collector is, moreover, fully confirmed by this analysis, which shows that its absence can lead to severe visual discomfort due to bright sun patches projected on the lateral walls. These patches become less sharp and bright as the sun azimuth relative to the facade decreases, since the portion of the direct sunlight that is spread by the anidolic components increases. It may therefore be possible to avoid the glaring risks that occur in absence of solar protection, by curving the sides' reflectors.

6.2. Human visual response tests

A group of 33 persons (13 women and 20 men) volunteered for human response tests carried out in the two daylighting modules. Their age ranged from 20 to 60 years (cf. Fig. 17). Although 2/3 of them were less than 30 years old, 55% wear medical glasses. A preliminary ergo-ophthalmic examination established that this population sample has eyesight features close to those of a medical data bank of 790 persons.

Three different types of response tests were submitted to the group of volunteers:

- a test of acuity based on black/white document reading, put horizontally on desk;
- a test of acuity based on VDT reading (besides its different orientation, the VDT is much more sensitive to veiling reflections because of its glass shield);
- a questionnaire of user acceptance.

The tests took place in mid-autumn between 1000 and 1600 legal time; daylighting was substantial during this period but not always sufficient. The same series of tests was submitted simultaneously to two subjects, each one placed in a room (cf. Fig. 18); after completion of their tasks, they changed room starting the same series of tests again at the other work place. Learning effects and impact of weather conditions were limited that way.

During the whole test procedure, the subjects were allowed to use electric light and solar protection at their convenience. Two lighting control modes were available:

- an automatic daylighting responsive control dimmer,
- a manually operated dimming controller.

Concerning glare control, it is important to note at that point that the test room is put at a disadvantage since its view window has no opaque blinds whereas the reference room is fitted-up with a venetian blind. This difference had however little impact since only two tests took place by sunny conditions. For the other cases, six persons had intermediate or variable weather and 25 had continuously overcast sky.

6.2.1. Acuity for document reading

The document presented to the subjects is a page of mat white paper (A4 format) containing a table of 96 'Landolt rings'[1] (acuity ≈ 0.6). Those figures have an opening, turned either to the left, to the right, up or downwards; the subjects have to count the number of items of each orientation, which

[1] This is a standard font for visual tests that looks like an opened ring, or like a 'C'.

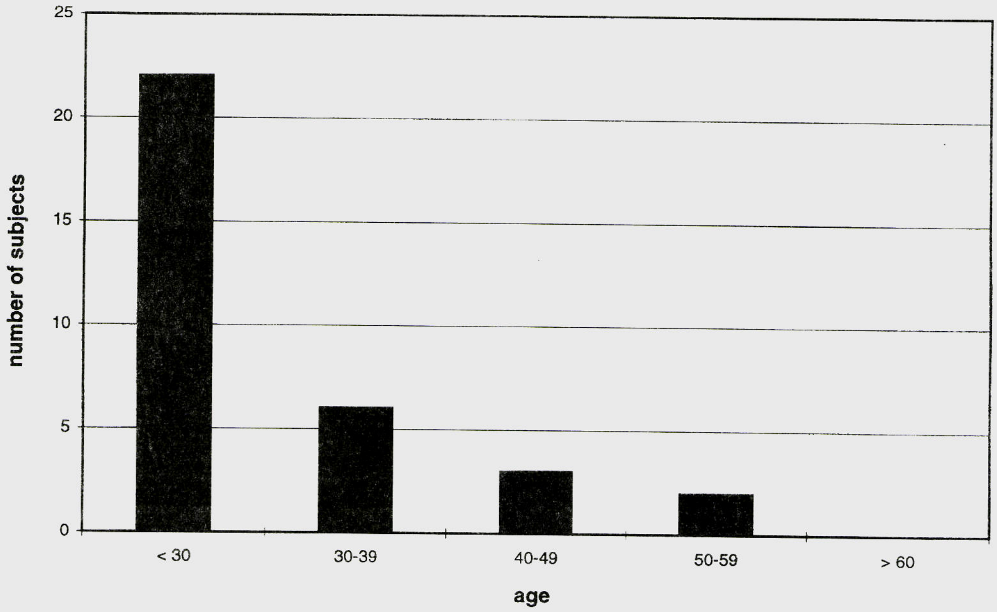


Fig. 17. The age distribution of the people submitted to the human response test.

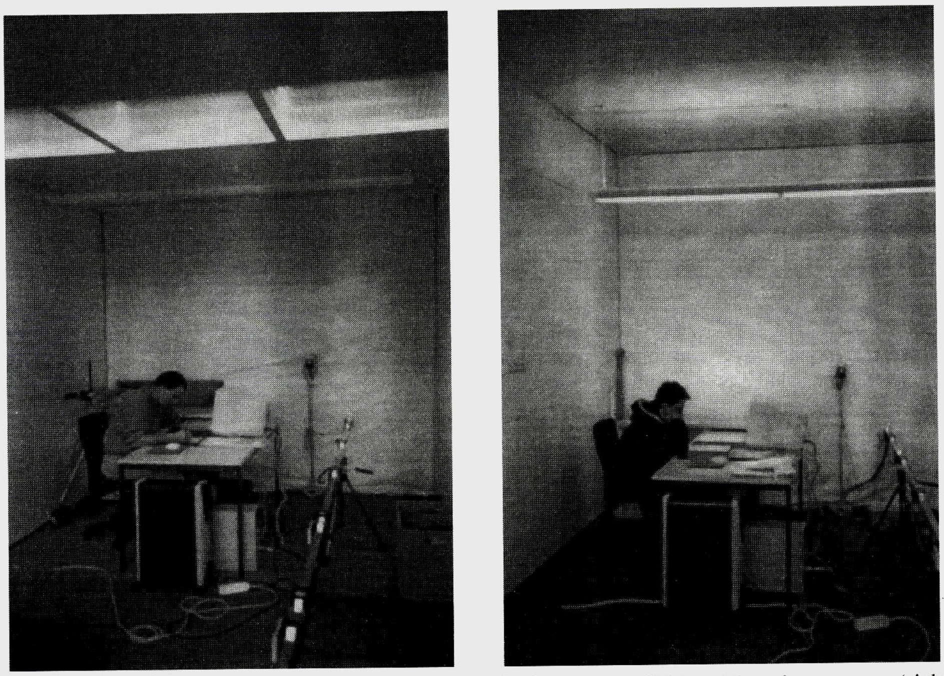


Fig. 18. View of subjects submitted to human response tests in the test room (left) and the reference room (right).

are randomly distributed. The rings were printed in grey with a density adjusted so that reading errors were likely to occur.

The number of errors made by the subjects in each room in determining the orientation of the Landolt rings were counted. The difference for each subject between the number of errors in each room was used as a measure of a possible modification of the users' visual performance due to the Anidolic Ceiling.

Fig. 19 gives the statistical distribution of the error difference; the average reaches -0.25 over 116 test samples (the reading error variable is sampled four times, one per ring orientation, and four tests had to be rejected for atypical behaviour). This negative value means that a subject makes on average 38% less reading errors in the room with an Anidolic Ceiling than in the reference room.

A statistical test was applied to these data to assess their significance. The following hypothesis, H_0 = the expected value (true mean value) of the difference of error is equal to zero, is tested against the following alternative hypothesis, H_1 = the expected value of the difference of error is negative.

The sample number being higher than 30, the average variation vs. sampling can be assimilated to a normal low. In

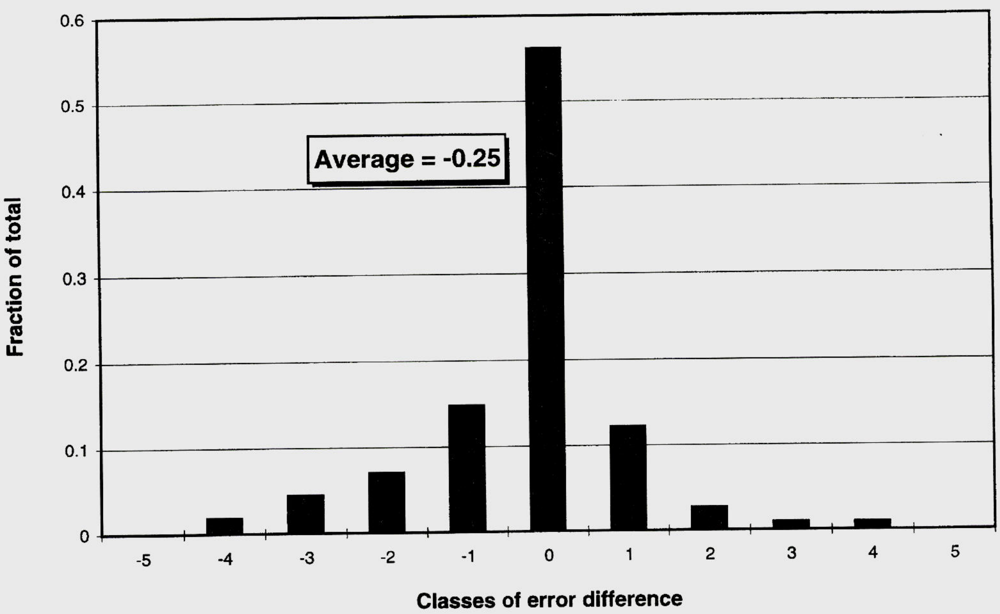


Fig. 19. The statistical distribution of the difference of reading errors for a subject in the two rooms (a negative value means that less reading errors occur in the test room as opposed to the reference room).

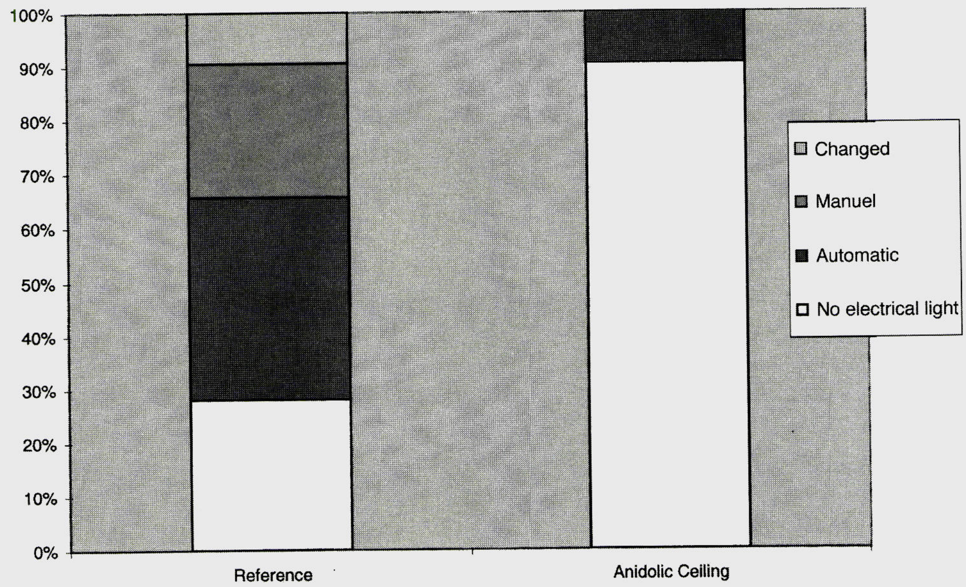


Fig. 20. The lighting mode used by the subjects in the different rooms (subjects could choose their lighting mode at their convenience).

the present situation, its expected value is supposed to be null (H_0), and its standard variation is estimated from the actual experimentation (value of 1.21). Calculations result in the following: a deviation as large as that experienced, or larger, would occur by chance in the expected negative direction (H_1) only about 2.5 times in 100. This probability is low enough to reject H_0 and accept H_1 with a confidence coefficient higher than 97%. The reduction of reading errors between the two rooms is therefore significant with regard to sampling random effects.

Further analysis of the lighting modes chosen by the subjects during their testing procedure showed a considerable difference between the two rooms, with daylighting preferred in the test room. Fig. 20 illustrates this.

Keeping within the original statistical sample, only the test data for which no electrical lighting was used were considered (36 samples). A greater difference in acuity was observed between the two rooms. The average difference of reading errors was found in this case to be equal to -0.42 and the confidence coefficient greater than 98%, showing the improvement due to the illumination increase brought to desk by the Anidolic Ceiling. Considering now the remaining cases (80 samples) for which the subject used electric light, at least in one of the rooms (mostly in the reference room, cf. Fig. 20), the average is still negative (-0.18) but the confidence coefficient stays underneath 77%.

6.2.2. Acuity for VDT readings

The subjects were requested to recognise a series of one digit numbers, automatically displayed on a VDT screen thanks to software developed by the LEV.

At the beginning of the procedure, the screen is fully white, as the contrast of the figure is null; by clicking the mouse, the subject can enhance the contrast step by step, up to the point where he recognises the number. If the person has succeeded, the program displays another number; in case of failure, the contrast is enhanced further until the number is recognised (the number of attempts was limited to three).

The size of the displayed number is decreased by one step every four numbers to increase the acuity (the subjects are requested to remain at a constant distance of 60 cm from the screen). In the considered sequence, the acuity steps required to read the figures were 0.25, 0.3, 0.5, 0.6 and 0.8; going any further was not possible due to the limited screen resolution (screen diagonal: 15 in, resolution: 1024×768 pixels, refreshing frequency: 75 Hz).

The users' performance was measured through determination of the threshold contrast of each reading; corresponding to the contrast value required by each subject until he recognises a figure. Conversion between contrast step and luminance was obtained through a preliminary calibration of the monitor, which was achieved using a fitting power function of the type 'gamma correction' [18].

Visual comfort at VDT requires a high control of veiling reflections; and since the blinds of the view window in the test room were not so opaque as the one of the reference room (venetian blind), a weather selection turned out to be necessary: the tests that occurred by continuously overcast sky are sorted out (25 cases over 33). The best level of confidence was found by focusing on the highest acuity tests (0.8). Those data show a diminution of the contrast threshold of 10% on average (cf. Fig. 21). The level of confidence is calculated according to the same significance test as the one used above for document reading. However, the sample number being much smaller (only 13 people reached the highest acuity level), the expected value is, this time, supposed to be distributed according to a Student–Fisher Law. The confidence coefficient is found to be above 98%.

The following conclusion can thus be advanced: under overcast sky conditions, less luminance contrast is necessary

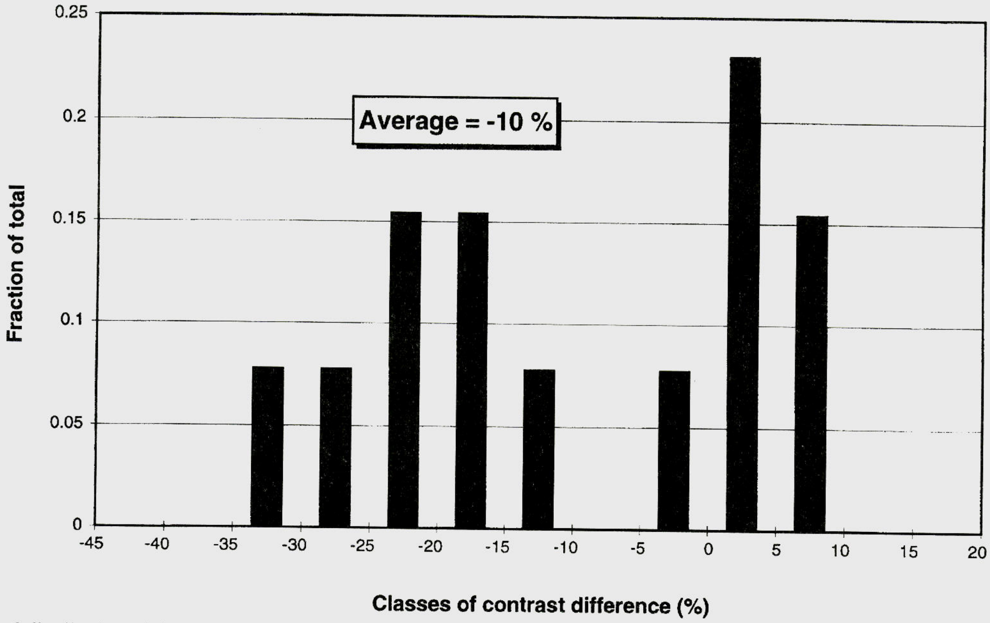


Fig. 21. The statistical distribution of the threshold contrast difference at highest acuity (0.8) in the two rooms for overcast skies (a negative value means a lower contrast threshold in the test room as opposed to the reference room).

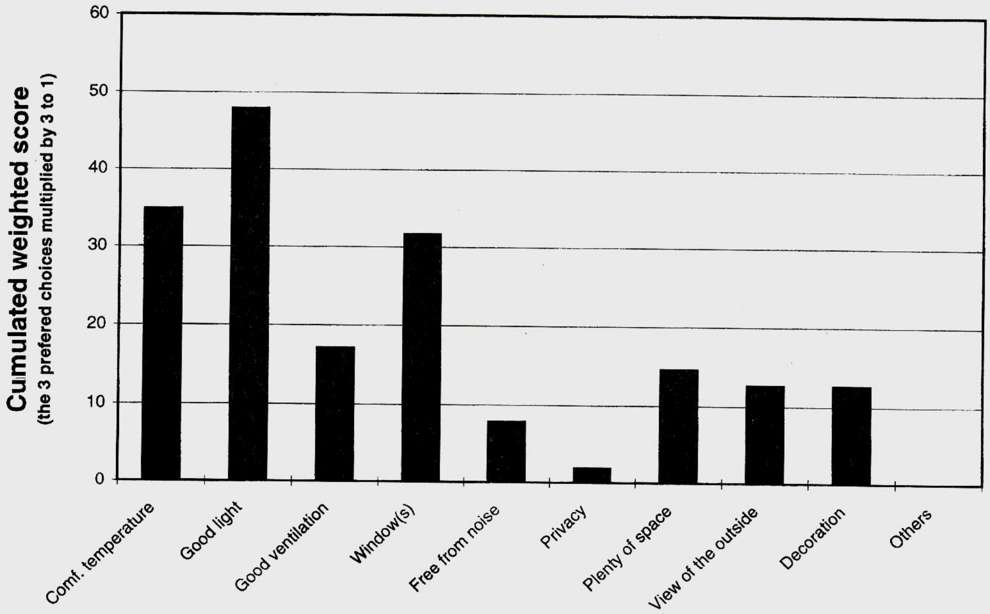


Fig. 22. Preferences of the subjects about comfort in buildings.

to read on a VDT screen in the test room than in the reference room. This tendency is consistent with the assessment of visual comfort; the visual performance enhancement is thus probably due to a more appropriate luminance ratio of the surroundings to the VDT screen.

6.2.3. User acceptance questionnaire

The subjects were asked to fill in a questionnaire regarding their opinion on comfort in buildings; furthermore, a personal appreciation of the particular luminous environment was requested. The questionnaire was based on a document elaborated by Hygge and Löfberg [19]. Most of the questions are multi-choice: the subject must either tick one of them or order his three best preferences; in this last case, scoring the votes is achieved through a weighted sum.

When asked about the physical features in making a workplace a pleasant one, the scores show a preference for lighting (cf. Fig. 22). This is all the more significant since the indoor temperature as well as the air renewal were sometimes at the lower bound of comfort conditions.

Fig. 23 shows, moreover, that 'good lighting conditions at the workplace' together with the 'presence of a good protection against glare' are the two aspects the users considered the most important when rating the blinds. Nevertheless, if

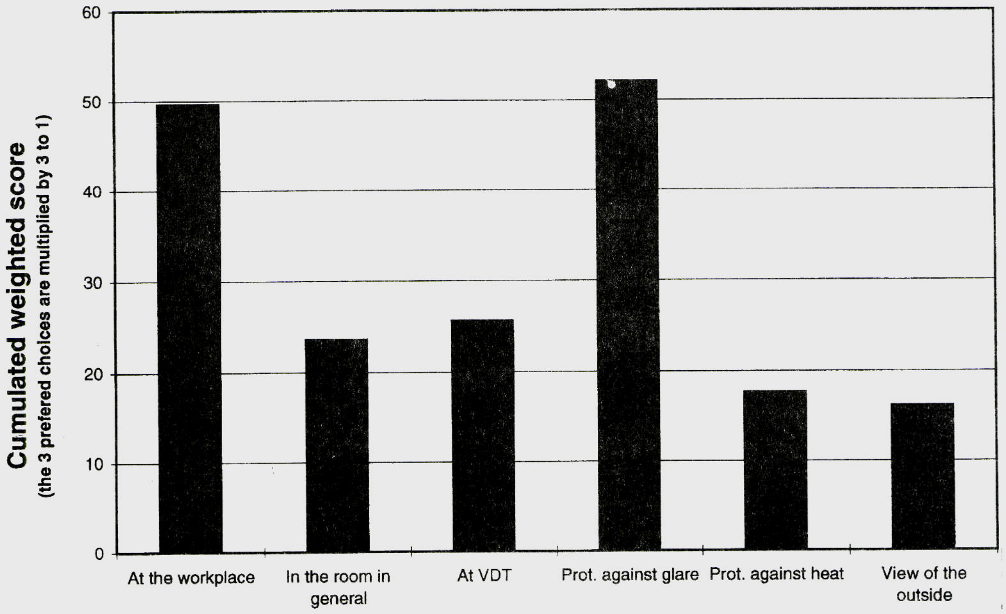


Fig. 23. Preferences of the subject about priorities for rating the blinds.

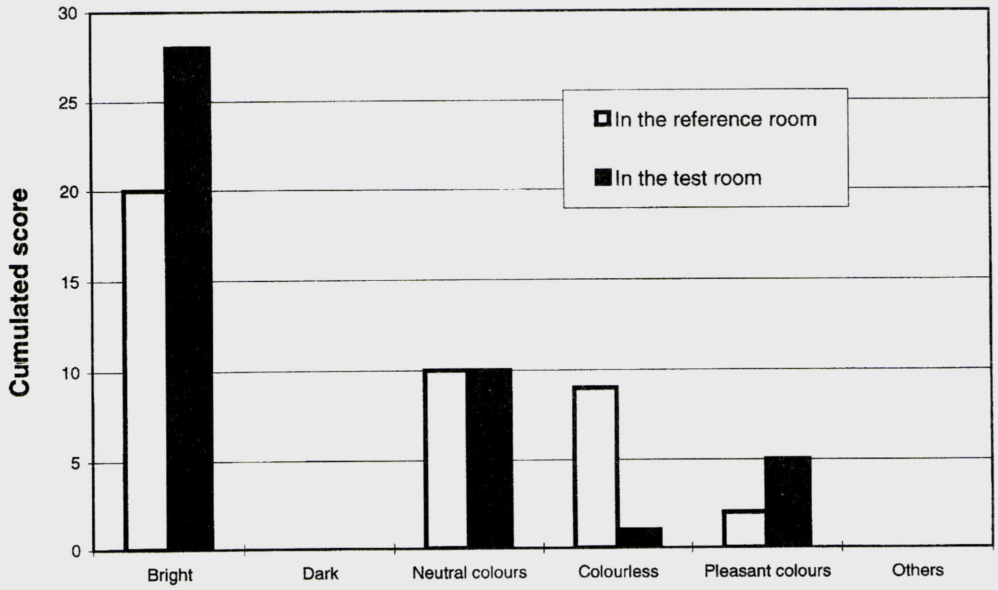


Fig. 24. Comparison of the perceived visual atmosphere by the subjects in the two office-rooms.

overcast sky had been less frequent, the protection functions would likely be at a better score, like perhaps also the view function.

Appreciation of light in function of its origin gives clear majority: 3/4 of the subjects find very important to have a window near the workplace, fast as many prefer the natural light to the artificial one or a combination of the two. The attraction to openings and daylight is all the more undeniable since test conditions exclude any claustrophobia reaction or orientation loss.

Concerning the personal appreciation of the particular luminous environment, no real differences appeared when asking about window advantages and disadvantages. However, the comparison of the perceived visual atmosphere in the two rooms led to the following interesting results (cf. Fig. 24):

- a brighter visual atmosphere was perceived in the test room;
- the colours in the test room were found more pleasant (although they were physically the same).

This second observation does not correspond to any physical reality: measures have shown indeed that the light-duct does not yield any significant change in the intrinsic colour of daylight under overcast sky conditions. The reason for this tendency would more likely be a psychological stimulation, either due to the orientation of the zenithal lighting, that is more natural than side lighting, or due to the *Kruithof effect*: by overcast sky, the colour temperature of daylight being close to 7000°K, the minimal satisfying illuminance is around 400 lux according to Kruithof [20]. In most common overcast sky situations ($E_{ext} \sim 10$ Klux), the daylight illuminance at the reference desk will be under this limit, whereas it will be satisfying at the test desk. This effect contributes, moreover, to explain why electric light is so much more often used in the reference room (cf. Fig. 20), its lower colour temperature (4100 K) reducing the Kruithof illuminance limit to a lower level (200 lux). Besides, daylight colour temperature could be taken into account at the design stage: choosing warm colour materials for the exit part of the light-duct (slightly gold tinted reflectors or glazing, wooden frame) may reinforce the improvement of visual comfort, and by effect on occupants behaviour, increase the electricity savings in lighting.

7. Conclusions

The construction of an Anidolic Ceiling prototype has allowed investigating the viability of intensive use of daylight in office buildings, for regions of temperate climate (high frequency of cloudy weather). A 6.6 m deep test room equipped with the prototype was compared to an identical room with a conventional double-glazing facade.

Monitoring under overcast sky conditions has demonstrated that the daylight factor, averaged in the rear half of the room, is multiplied by 1.7; this outstanding performance allows electricity savings of a third of the consumption for lighting. The experiments were carried out at a place far from any elevation. By overcast sky, this condition brings about an important over evaluation of the daylight factor in the rear half of the reference room with regard to most urban situations. Thanks to computer simulations, it has been shown that, when an obstruction of 40° is put in front of the facades, the enhancement ratio of the daylight factor can increase up to three, doubling the energy saving measured in the case of a clear horizon (estimated from [14]).

Visual comfort measurements showed that, by overcast sky, the Anidolic Ceiling supplies lighting of superior quality to that obtained with facade glazing. By sunshine on the facade, the solar protection is however essential. Furthermore, 33 people tested both rooms one after the other. They were submitted to a couple of visual acuity tests on printed paper and on a computer screen and had to fill in a questionnaire. A statistical comparative study of the results puts under light a significant reduction of reading errors both on paper and on the screen. Besides, the questionnaire has confirmed a large preference of daylighting; it has also revealed a better appreciation of the visual environment in the office equipped with the Anidolic Ceiling.

The type of integration investigated, ceiling embedding, should find promising architectural application in the retrofitting of office building (cf. Fig. 25). Typical open space offices of the sixties could provide excellent integration opportunities for such systems due to their generally large recessed ceilings.

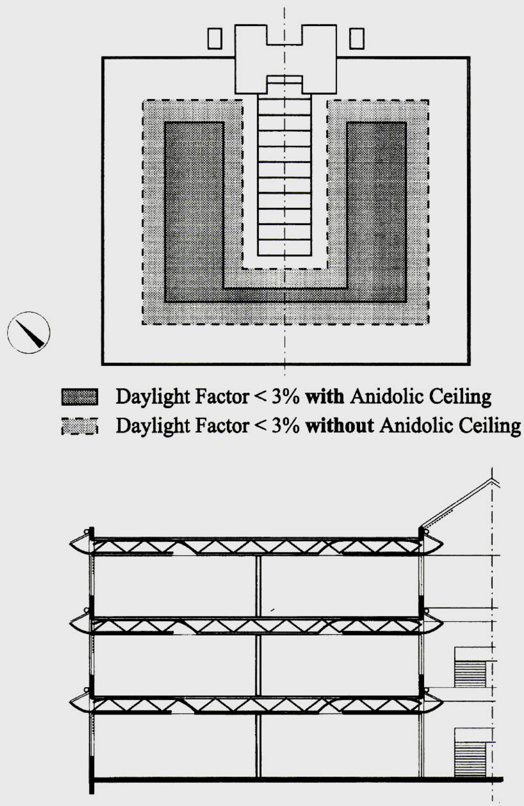


Fig. 25. The possibility of integration of an Anidolic Ceiling in case of retrofitting of large open space offices.

8. List of symbols, initials and acronyms

CPC	Compound Parabolic Concentrator
D_{rear}	Space average of the daylight factor in the rear part of the room, from 3.7 to 6.4 m
$D_{rearRef}$	D_{rear} in the reference room
$D_{rearTest}$	D_{rear} in the test room
Diff/Glo	Ratio of the diffuse horizontal irradiance to the global one
E	Illuminance
E_0	Illuminance level required on the working plane
E_{ext}	Outside horizontal illuminance
E_{hdext}	Half-day average of the variable E_{ext}, over the period of electric lighting only
PPD	Probable Percentage of Dissatisfied
VDT	Video Display Terminal
ε	Ratio of E_{ext} to the external horizontal illuminance necessary to switch off the rear light of the reference room; $\varepsilon = E_{ext} \cdot D_{rearRef}/E_0$
ε_{hd}	Half-day average of the variable ε, over the period of electric lighting only
ρ_r	Regular reflectance

τ_r	Regular remittance
SAI	Sky Asymmetry Index = ratio of the standard deviation of the illuminance values of the four facades to their average
SAI_{hd}	Half-day average of the variable SAI, over the period of electric lighting only
SF_{hd}	Half-day Saving Fraction: fraction of total energy saving

Acknowledgements

The authors wish to thank Mr. A. Müller, architect, who was in charge of the construction of the Anidolic, Ceiling, Messrs. P. Loesch and U. Meierhofer for their work in building the prototype and installing the monitoring set-up, as well as Messrs. R. Compagnon and L. Michel for their advice. Thanks are also addressed to all the test volunteers. This research was funded by the Swiss Federal Fund for Education and Science.

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