Revival

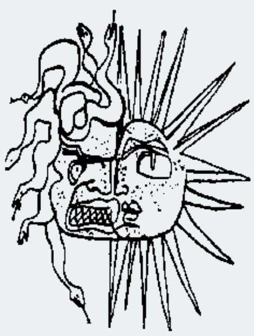
TECHNICAL**MONOGRAPH** 4

High performance daylighting - light and shade

This technical monograph is one of a set produced as part of the 'REVIVAL' project – an EU Energie Programme supported demonstration project of energy efficient and sustainable refurbishment of non-domestic buildings in Europe. The monographs explore some of the main energy and comfort issues which arose during the Design Forums held with each of the six sites. The four monographs are entitled:

- **Thermal mass and phase change materials in buildings**
- **Adaptive thermal comfort standards and controls**
- **Natural ventilation strategies for refurbishment projects**
- **High performance daylighting**

▶ **Figure 1**
The two faces of the Sun by Le Corbusier



Refurbishment often involves the upgrading of glazing. This can range from straightforward replacement of the glazing material to the reduction or enlargement of the apertures. The installation of shading systems is also common, and again this can range from minor interventions such as roller-blinds, to large external structures. In the latter case, the design is often driven by architectural decisions rather than functional performance. However the daylighting will be affected, and in most cases, there will be an opportunity for improvement.

What is high performance daylighting?

We are all familiar with the problem facing the designer – large windows to let in lots of daylight and useful solar gains in winter, or small windows to conserve heat and prevent overheating from unwanted solar gains in summer. All too often, we observe in summer the 'blinds down - lights on' syndrome, and the presence of massive and costly shading structures which not only shade unwanted sun, but also cut out valuable daylight and obstruct views. It is also common practice to orientate the main glazed façade of buildings south (in the northern hemisphere) to maximise solar gain in winter.

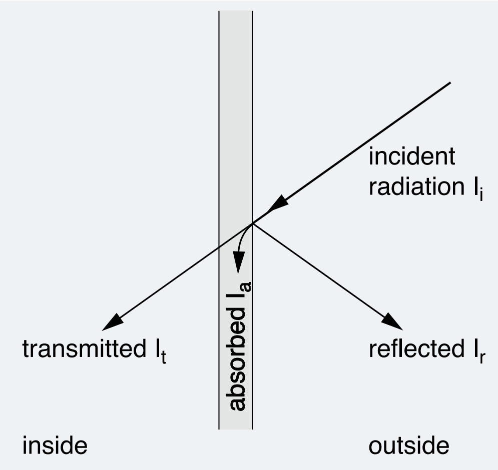
Two recent technical developments have contributed to a solution but not fully solved it. Firstly, the U-value of modern glazing systems, using low-emissivity surfaces with inert gas filled cavities, can be as low as 1.0 $W/m^{2o}K$, 5 – 6 times better than single glazing. Secondly, 'high performance' glazing of this type may also have selective transmission to radiation that, by having lower transmittance in invisible part of the spectrum, reduces solar gain to a greater extent than the visible daylight.

However, this property is fixed, and clearly in the heating season, when thermal gains may be used to offset heating loads, this property is counter-productive. Given that most European buildings have both heating and [potentially] overheating seasons, how does the designer arrive at a good solution for year round performance?

Shading devices provide opportunities to both modulate and spatially re-direct incoming radiation. Furthermore, if movable, they can alter their function according to seasonal changes and even hourly sky conditions. This monograph sets out the technical principles for developing good solutions involving both high performance glazing materials and shading devices.

Glazing

The spectrum of daylight
The Sun is the original source of daylight; solar radiation falls on the outer atmosphere with an intensity of about 1.6 kW/m^2, where it is reflected, absorbed and scattered. This reduces the intensity of the direct beam to around 800W/m^2 by the time it reaches earth. About 50% of the energy lies in the visible region, the remainder being in the ultra-violet and infra-red spectrum, as shown in figure 2. In regions where clear skies do not predominate, useful daylight consists mainly of radiation scattered from clouds and the atmosphere, and will typically be about 50 – 150 W/m^2. Both absorption and scattering change the spectral content of the sunlight; particles of the atmosphere scatter shorter wavelengths (the blue end of the spectrum) preferentially. Thus diffuse daylight from the sky is slightly bluer than direct sunlight. The essential issue is however, that only the visible part of the spectrum provides



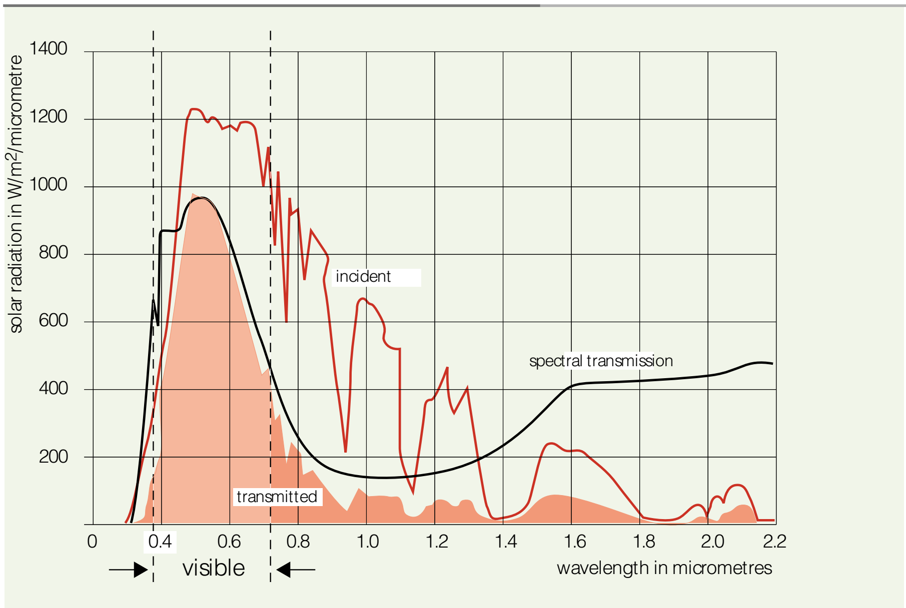


Figure 2
The spectral distribution of sunlight. Only about half of the energy lies in the visible region. The spectral transmission of glass, and the resulting transmitted spectrum (shaded) is also shown.

Figure 3
Incident radiation is split into three components – transmitted, reflected and absorbed

daylight useful for visual tasks, whilst the whole spectrum, visible and invisible, contributes to heat gains when absorbed in the room.

The energy balance at glazing
Figure 3 shows the energy balance of the radiation incident on the glazing. The radiation falling on the glazing surface becomes three components – a reflected component I_r, a transmitted component I_t and an absorbed component I_a. For normal clear glazing, the reflected component is about 15% of the incident value but this value increases strongly when the angle of incidence increases beyond about 60°. The transmitted component is about 80% of the incident radiation, leaving 5% absorbed by the glazing.

The transmittance is the ratio of the transmitted component to the incidence component, often quoted as a percentage.

Two other types of glass are commonly encountered, tinted and reflective. Tinted or absorptive glass contains pigments to increase the absorption. This reduces the transmittance, typically from 40% to as low as 10%. The absorbed energy heats up the glass and this heat is partly conveyed into the room and partly to the outside by radiation and convection.

Reflective glass has a thin metallic or semi-conducting coating which increases the reflected component, also reducing the transmission. However in this case, the energy is reflected away from the glass, not absorbed by it, and thus causes no heat gains to the room.

Glasses which have both reflective and absorptive properties have been available for about three decades. However, these materials reduced the visible part of the spectrum more than the non-visible. In spite of the glasses being marketed as having a beneficial environmental performance, there is no advantage in having a large area of low transmittance glass compared with a smaller area of normal glazing. Indeed, there is a disadvantage in that the glazing would have a much larger U-value than a well-insulated opaque envelope that could have replaced it.

High performance glazing products
Glasses which are referred to as "high performance" have the important property that the transmittance in the invisible spectrum (the infra-red and the ultra-violet) is significantly less than in the visible. Although the thermal gains due to the absorption of the visible light remains the same (for a given level of illuminance), gains from the invisible part of the spectrum are reduced. Thus the light can be regarded as "cooler", or put more scientifically, to be of *higher luminous efficacy*.

This is illustrated in the figure 4 which shows the heat gains to a $12m^2$ room, for different glazing materials. In each case, the area of glazing is adjusted to give an average illuminance of 300 lux. The x-axis shows the ratio of total transmittance T_t to the visible transmittance T_v. For high performance glass, the ratio T_t/T_v is less than one. However, even if none of the invisible radiation were transmitted, this ratio could not be below 0.5, since about half of the thermal effect of solar radiation is due to visible radiation. This is shown as the theoretical limit on the graph. Materials with ratios greater than one actually worsen the situation, since, as the graph shows, more heat is generated in the room for the same amount of light.

This is also shown in figure 5 where the actual solar gains are calculated for a 16m² room. For the clear glazing the area has been set at 3.2 m² to provide a minimum daylight factor of 2%, a typical value for a well daylit room. The area has been adjusted to compensate for the reduced transmission in the other cases.

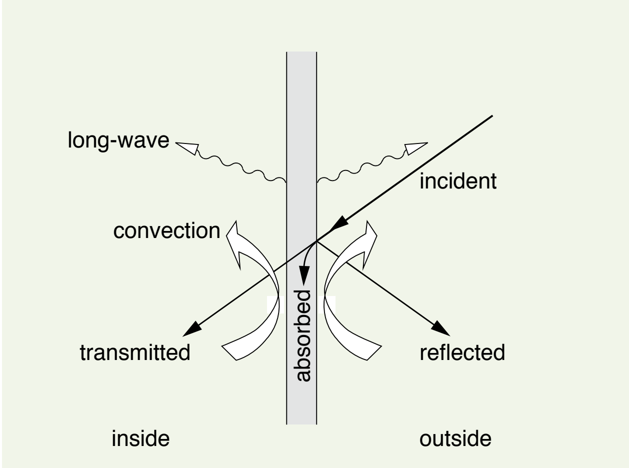
Energy re-distribution

It is the absorption of the solar radiation that causes the thermal gains, and this takes place on the surfaces of the room, as well as in the glazing itself. Figure 6 shows that the heat generated in the glazing is redistributed, partly inside, and partly outside, by convection and radiation. Within the room the process is complex and includes short-wave reflected radiation (visible, IR and UV) some of which 'escapes' back out through the glazing. However, most of the short wave IR and all of the long-wave IR is absorbed by normal glass. This, creates the diodic effect commonly known as the greenhouse effect.

Low-emissivity glasses (low-e)

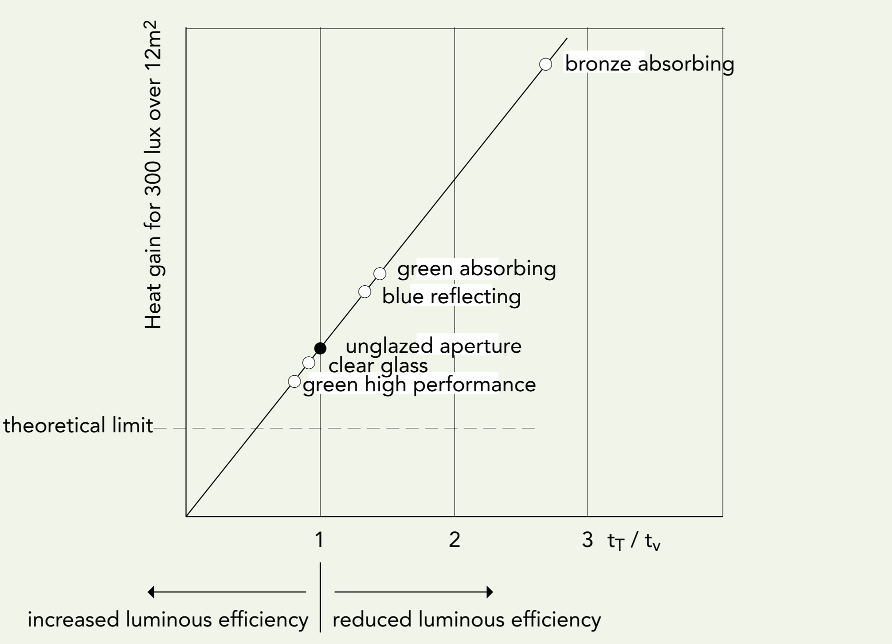
Normal glass absorbs all long wave radiation (as a black surface does to visible radiation). It is also of high emissivity, that means that it emits almost the maximum amount of long-wave radiation possible for a given temperature. Low-e glazing has been coated with a very thin electrically conducting layer and this renders it reflective to long-wave radiation and by the same mechanism, reduces the emitted radiation, compared with normal glass.

The original use of low-e glass was to reduce the heat loss by radiation during the heating season, as shown in figure 7. It is usually used as part of double glazing, partly to protect the coated surface, and partly to ensure that there is still air adjacent to the low-e surface, to realise the maximum benefit

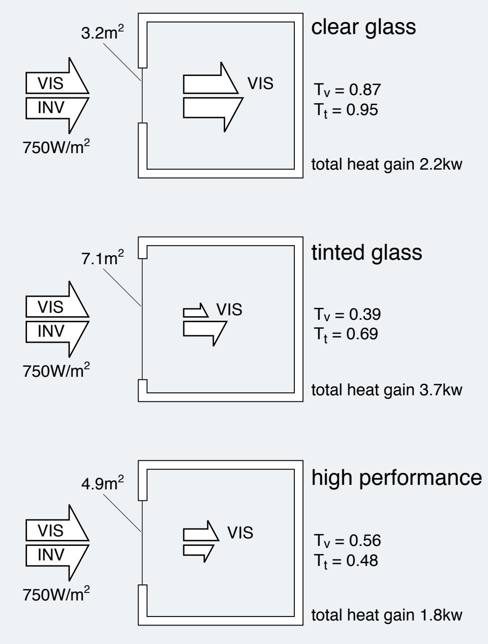


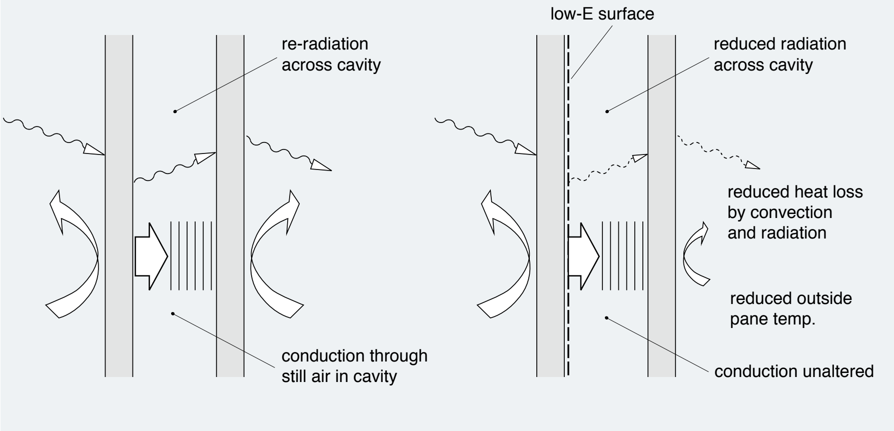
▲ **Figure 6**
Absorbed radiation hats up the glass. This heat is lost by longwave radiation and convection to the room and to outside.

▼ **Figure 4**
Solar heat gain plotted against the ratio of total transmittance to visible transmittance, for a given average illuminance of 300 lux



▼ **Figure 5**
The impact of glazing type on solar gain for a 4m x 4m sidelit room with a minimum Daylight Factor of 2%. The glazing area of 3.2 m² is adjusted to account for the reduced transmission of the tinted and high performance glass, to 7.1 and 4.9 m² respectively. The solar gain is calculated from: solar gain = 0 .75 x (area glaz) x $T_{t\,kW}$





▲ Figure 7
The effect of a low emissivity coating on the inside of the cavity of double glazing. Heat transfer by long-wave radiation from the inner to outer pane is reduced

For example, the typical value of 2.8 for normal double glazing can be reduced to about 1.8 when a single internal surface is low-e. Convective heat transfer can be reduced by filling with heavy inert gas (argon) and this reduces the U-value further to about 1.0.

Recently, hard durable low-e coatings have been developed which can be applied to single glazing. This can reduce the U value from 6.0 to about 4.0 in still air.

Low-e surfaces can also contribute to reducing unwanted solar gains by reducing the heat transmitted from the outer pane to the inner pane by long wave radiation.

Dynamic transmittance, photo-, thermo, and electro-chromic glasses
The materials described previously have fixed properties. Thus they cannot respond to current conditions, and have to be specified as a compromise solution for long-term average conditions. One parameter which can be controlled dynamically is the transmittance. Photo-chromic materials reduce their transmittance as the light level increases. They are the most familiar, being in common use for spectacles. Costs still prevent their widespread use in buildings. However, their optical performance is not of the selective type, which means that glazing controlled in this way would suffer more solar gain than if controlled by conventional opaque shading devices.

Thermo-chromic materials, reducing their transmittance in response to an increase in temperature, are similar in that they are passive elements, responding to the agent (solar radiation), which needs to be controlled. However, in both cases, the materials are reactive, and cannot anticipate conditions, as well as having poor spectral transmittance characteristics.

Electro-chromatic materials are usually liquid crystal systems, similar in principle to those used for data display, responding to the application of an electric field. These offer the great advantage that they can be switched and modulated with control intelligence. However, they are not spectrally selective and so their thermal performance would not be particularly good.

Solar strategies
Materials with selective transmittance, as described above, are clearly aimed at reducing heat gains associated with useful daylight.
In predominantly warm climates with mild winters, this is a priority. In most of these cases larger energy savings will be made by reducing cooling loads by shading, than reducing heating loads with solar gains. Many European climates however, also have a significant heating demand in winter. ‘Solar strategies’, where the building is designed to encourage winter solar gains, have long been seen as an important means of energy conservation.

The degree to which this is true is highly dependent on factors such as the detailed climate, the use pattern of the building and the presence of other sources of heat gain, the standard of insulation, and control strategy.
It is probably fair to say that there are many cases where designers have tried too hard to maximise winter solar gain for only a modest reduction in heating load at the expense of other environmental problems; in particular overheating in summer.

Shading devices

Shading devices assist in the management of solar gains and useful daylight. Unlike glazing materials with fixed properties, shading devices – overhangs, fins, blinds, louvers etc, offer two ways in which they can respond to seasonal conditions.

Firstly, using simple geometry, fixed devices can intercept more solar radiation from higher angles than from lower angles, thereby approximately synchronising with the need for winter heating and the risk of summer overheating. Overhangs and fixed horizontal louvers, use this well known principle, which can be found in many examples of vernacular as well as contemporary architecture.

Secondly, moveable devices can be adjusted to modulate their transmittance – e.g. the opening and closing of louvers, or the raising and lowering of a low transmittance blind. The range of modulation can be large – in principle between 0 and 100%, as in the case of an opaque blind which can be fully retracted or fully deployed over a window. These categories and their significance to performance are described below.

Daylight redistribution

Shading devices have one more important property; due to the reflection of light from surfaces and/or the obscuration of light from specific directions, certain devices can improve the distribution of daylight in a room. Sidelit rooms from plain apertures are very unevenly lit, as shown in figure 8. This means that in order that the minimum illuminance is sufficient, the part of the room near to the window has to be over-illuminated. At times of zero heating load this over-illumination serves no useful purpose, but will contribute to overheating and probably glare.

If the light distribution can be improved the total amount of light flux entering the room, (and the invisible radiation accompanying it), can be reduced. Thus the ideal shading device not only modulates the transmittance of the window, compensating for conditions of high radiation levels, but also improves the efficiency of distribution. Figure 8 shows how a light shelf reduces illuminance close to the window more than at the back of the room. Thus, the unwanted part of the incident radiation is reflected away reducing solar gain. Horizontal louvres can work in a similar way.

How can we assess performance?

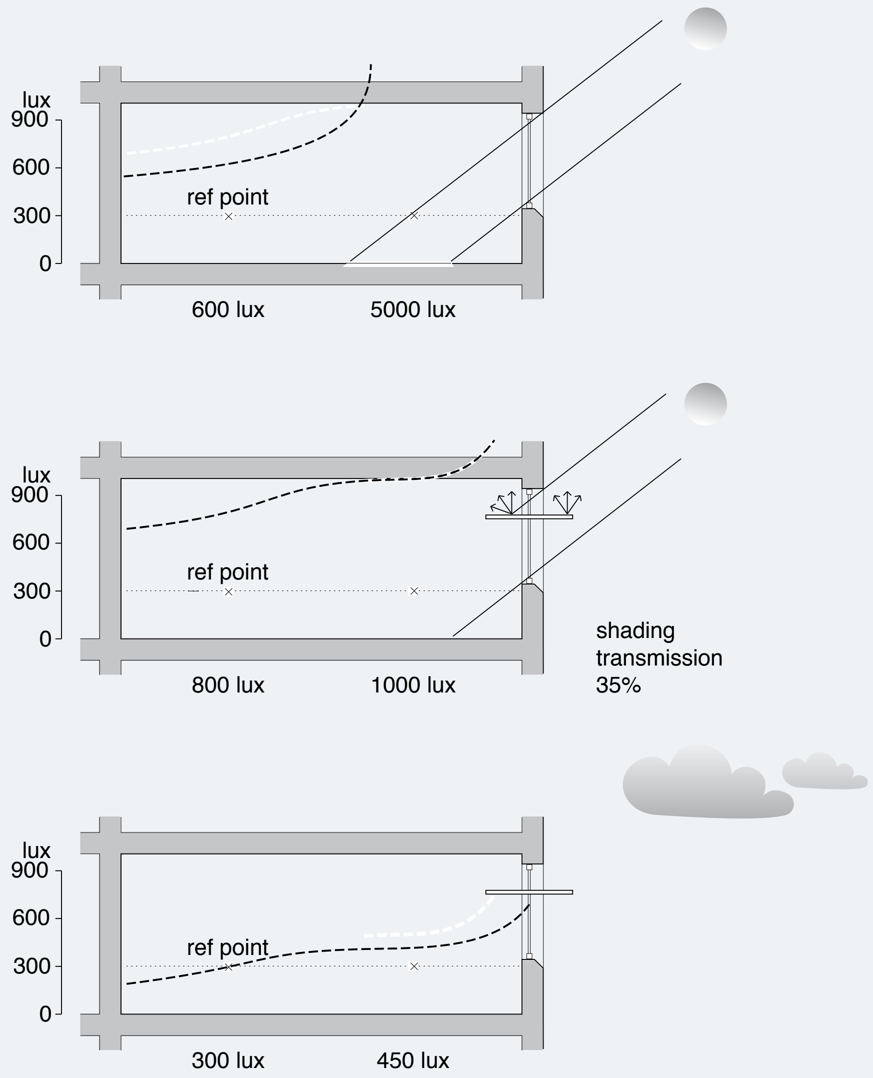
If we consider the window, glazing and shading device as a *daylighting system*, then it is a useful concept to consider the *luminous efficacy* of this system – i.e.

Luminous efficacy =

$$\frac{\textbf{total useful light flux delivered to the work plane}}{\textbf{total radiation energy entering the room}}$$

Note that the definition of *useful* flux excludes illuminance above a datum value, i.e. a value that is considered to be sufficient for the function of the room.

The Luminous efficacy of daylight is about 110 lumens/Watt. This would be a theoretical maximum for a window system, i.e. providing an even illuminance at the datum value. In reality, a normal sidelit room, due to its non-uniformity could have a value as low as 30 lumens/Watt, placing it somewhere between tungsten and conventional florescent lighting. From an overheating point of view, we can see that there might be some justification for the "blinds down – lights on" mode of operation.



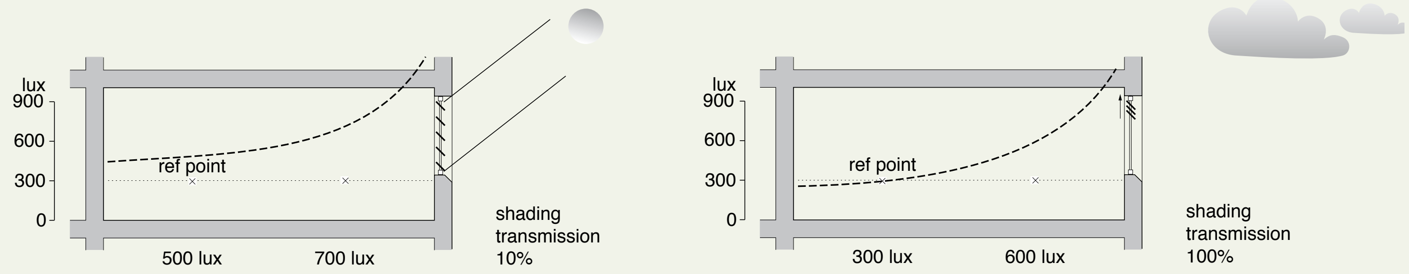
▲ Figure 8
Shows the non-uniformity of illuminance in a side-lit room (top) and the effect of a light-shelf in both sunny and cloudy conditions. The light-shelf reduces the over-illumination near the window.

Shading types – Dynamic performance

It is important to consider the performance of the system over different conditions – a solution that is optimum for a given combination of sky brightness and distribution may perform badly at other times. In particular, the ability to reduce the risk of overheating at times of plentiful solar radiation in summer, must be balanced against the ability to provide sufficient illuminance within the room, and possible useful solar gains, during the winter.

To assist in further understanding of this problem, it is useful to define four shading types –

Type 1 Retractable blinds, shutters and louvers.
This type does not affect the availability of useful daylight, provide they are under "sensible control" – i.e. they are deployed when there is a surplus of radiation, and retracted when there is minimal radiation. In this way they will not lead to an



▲ **Figure 9**
Retractable shading should be deployed only when there is an excess of daylight illuminance, thus not affecting the limiting case when lights have to be switched on.

earlier switch on time for artificial lighting, and thus will not increase lighting energy.
On the other hand they will reduce overheating probability or cooling energy, as shown in figure 9.

Type 2 Fixed redistribution devices – overhangs, light shelves etc.
These devices reduce the total radiation passing through the window system, but owing to their being directionally selective, do not reduce the illuminance level at the switch-on reference point – i.e. they improve the luminous efficacy of the system, since they only reduce over illumination. This has already been shown in figure 8. Fixed devices of this type may reduce useful illumination compared with the unshaded aperture, but this can be compensated by increasing the aperture size.

Type 3 Reduced transmission selective (high performance) glazing.
This increases the luminous efficacy of the daylight (light to heat ratio). Slight reductions in illuminance at the reference point can be compensated by increased glazing areas, figure 10.

Type 4 Fixed obstructing screens and non-selective reduced transmission glazing (e.g. tinted, reflective, or fritted glass)
These devices reduce all radiation visible and non-visible, at all times, in the same proportion. Thus they will reduce the illumination at the reference point and lead to an earlier call for artificial light, as shown in figure 11. They offer no technical advantage over having a smaller unshaded aperture.

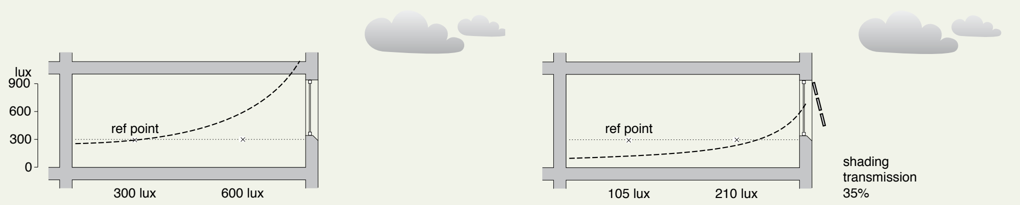
High performance daylighting in refurbishment projects

Glazing Replacement
Glazing replacement is commonly part of envelope refurbishment. This is most often to improve the thermal insulation performance, replacing single glazing with double or double low-e glazing. The main benefits of this will be in reduced heating load, but there should also be a significant improvement in comfort. This is due both to the reduced radiant losses to the glass surface, and the reduction of cold downdraughts, as illustrated in fig 13.

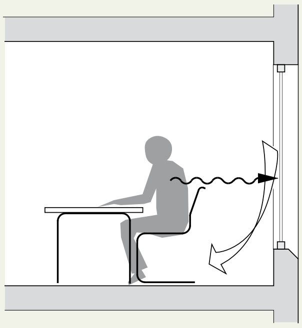
Low-e coatings are of two types (a) the hard ceramic coating and (b) the soft metallic coating. The hard coating has a slightly poorer performance than the soft coating, but it has

▼ **Figure 10**
Low-e glazing in the refurbished classrooms at Chevrollier

▼ **Figure 11**
Fixed screens and reduced transmission glazing (tinted, reflective or fritted) reduce the illuminance throughout the room and therefore increase the need for artificial lighting



▶ **Figure 12**
Fixed external louvres may improve light uniformity but interfere with view out



▲ **Figure 13**
Cold radiation and downdraughts are reduced by the use of low-e coatings thereby increasing comfort as well as reducing heat loss

the advantage that it is durable enough to be unprotected, i.e. it can be used in single glazing. This may have real advantages in the refurbishment of historic buildings where the original framing (glazing bars) is to be retained. Although, the reduction of U-value from 6 W/m^{2o}K to 4 W/m^{2o}K is much less than the 2 W/m^{2o}K achievable with low-e double glazing, this 33% reduction could be significant in a building with large areas of glazing.

Where the retrofitting of double glazing is possible, then the soft coating can be used. Units with argon filled cavities have U-values, as low as 1.2 W/m^{2o}K.

When assessing the thermal benefit of replacement double glazing, the thermal performance of the whole glazed envelope, i.e. including the glazing bars, must be considered. Framing systems of steel or aluminium without thermal breaks, and with small panes and therefore a larger area of framing, can have much reduced performance due to conduction through the framing itself. For example an aluminium frame with no thermal break and occupying only 10% of the aperture will increase the U-value of the glazing from 1.5 to 2.2 W/m^{2o}K.

Modifying apertures

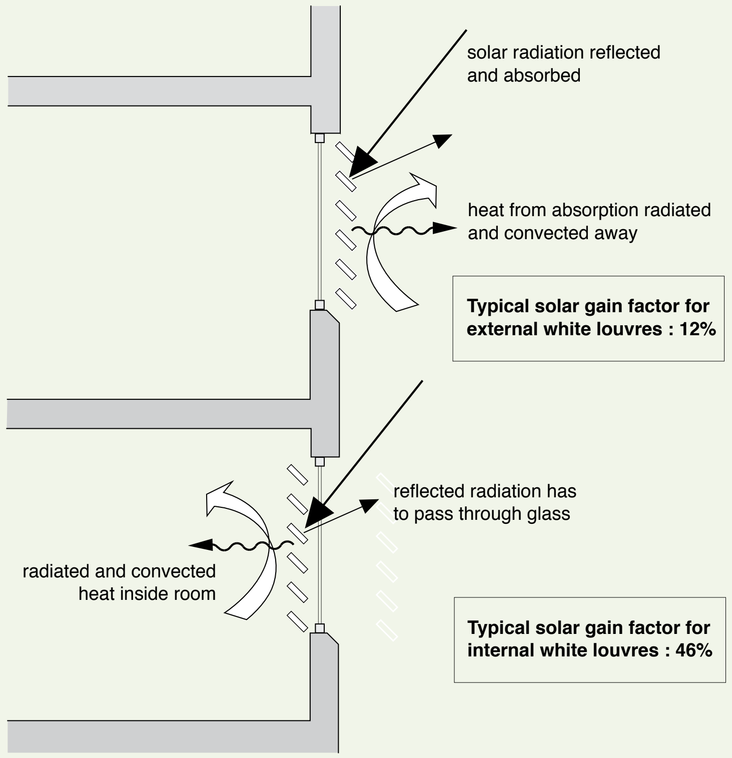
Many buildings from the 50s onwards, that are now being considered for refurbishment, have large areas of glazing. In many cases this is single glazing, and would thus be possible candidates for glazing replacement. If aesthetic considerations allow it, a reduction of the aperture area could be considered. This will have several advantages – reducing heat loss and unwanted solar gain, reducing glazing costs, reducing shading costs, and in some cases supporting interior remodelling.
Since the new opaque envelope can have U-values as low as 0.2 W/m^{2o}K, the impact on the average U-value can be significant. For example, if the 70% double glazing of a façade is reduced to 35%, with an opaque material with U-value of 0.2 W/m^{2o}K, the average U-value of the original aperture would be reduced from 2.8 W/m^{2o}K to 1.5 W/m^{2o}K.

Although 35% glazing can be shown to provide adequate daylighting for rooms of up to 6m deep, care has to be taken with how the distribution of glazing is altered. General rules of thumb are given below for spaces with a 3m floor to ceiling height–

- Sill heights should not be raised above 1m from floor level.
- Glazing in the upper part of the wall is more effective than the lower (except when there are deep overhangs)
- Horizontal distance between glazed areas should not exceed 3m (or 2m from crosswalls in cellular offices
- There may be a case for splitting the viewing and daylighting function

There may be cases for increasing the glazed area, where daylighting is demonstrably inadequate. However, other causes for poor daylight performance should be eliminated first – e.g. low transmission of glass, obstruction due to framing or poorly designed shading devices, low reflectance of interior surfaces, or internal obstructions.

There may be cases for changing the distribution of glazing by making new apertures. Single-storey buildings and top floors offer a good opportunity for this. Small areas of rooflighting over a deep plan can make a dramatic improvement in daylight distribution, and therefore, on the luminous efficacy of the system. However, in warm climates, rooflights should never be un-shaded horizontal glazed apertures, but always structures with apertures sloping away from the equator.



▲ **Figure 14**
External versus internal shading

Shading options
Many buildings lack shading. This may either be due to deliberate design intention, i.e. that the shading devices have been seen by the architect as an intrusion on the design concept, or due to economies. In some cases they simply weren't considered due to poor understanding of the problem.

Many of the buildings where the architectural specification has not included shading provision, will have had shading retro-fitted at some stage. Most commonly this will be internal curtains, blinds or louvres, but at worst, pieces of paper stuck onto the glass by desperate occupants. The installations are often poorly integrated with the window design, obstructing controls and interfering with ventilation, and are usually poorly maintained. These experiences give shading a poor reputation.

These notes are intended to assist in strategic decisions about shading. Detailed design and specification should use analytical design tools to assess the performance quantitatively.

Options for shading fall into four categories – **External, Internal, Inter-pane and Integrated.**

It is well known that the thermal performance of external shading is superior to internal shading, since re-emitted heat is lost to the outside, rather than into the room, as shown in figure 14. However, internal shading is usually cheaper and easier to control.

Interpane shading refers to devices held between panes, or in the cavity of a 'double skin' envelope. These systems have the advantage that the shading device is protected from weather, dust, and mechanical damage. It is important that the design of the cavity permits adequate ventilation to the shading elements.

Integrated refers to devices such as lightshelves and prismatic systems which explicitly address the daylight distribution function as well as selective shading.

External Shading
External shading broadly falls into the following types –

- Overhangs (fixed or retractable)
- Louvres (fixed, adjustable, retractable)
- Fins (fixed, adjustable)
- Blinds (retractable)
- Perforated screens (fixed)

fixed – fixed

adjustable – remains in position but radiation transmission can be modulated e.g. altering angle of louvre.

retractable – can be removed completely from the aperture

A summary of their properties is given in the table below. When using the table please note the following.

Nat vent limiting conditions refers to situations requiring the shading to be deployed, i.e. when there is an overheating risk.

Daylight limiting conditions refers to minimal daylight availability when there would be no requirement for shading.

Adjustable louvres and fins will have poor view performance and poor natural ventilation performance, if completely closed.

Orientation ***all*** implies that performance is not orientation-sensitive, although in general, there would be no demand for shading on facades orientated 360 +/- 45.

Figure 15 Office in Athens where internal louvre interfere with the opening windows and ventilation.

Internal shading. This is often the choice for retrofit. Options are limited to louvres (Venetian blinds) and roller blinds of translucent material.

Horizontal louvres offer some possibility for improved light distribution by using a combination of high and low reflectance finishes. If the upper surface is light, and the lower surface dark, light will tend to be directed upwards towards the ceiling, thereby improving the illumination at the back of the room. Some, proprietary systems use specially shaped louvres with specular (mirror) reflecting surfaces, in order to further improve the performance.

Most internal louvre systems are retractable, allowing maximum daylight transmission at times of limiting daylight availability. This also permits cleaning. Whilst open louvres can allow a good flow of air, they should be anchored top and bottom to prevent movement and noise. However, access to window opening controls must be provided. These conflicts often result in low cost simple installations being of poor functional quality, as shown in figure 15.

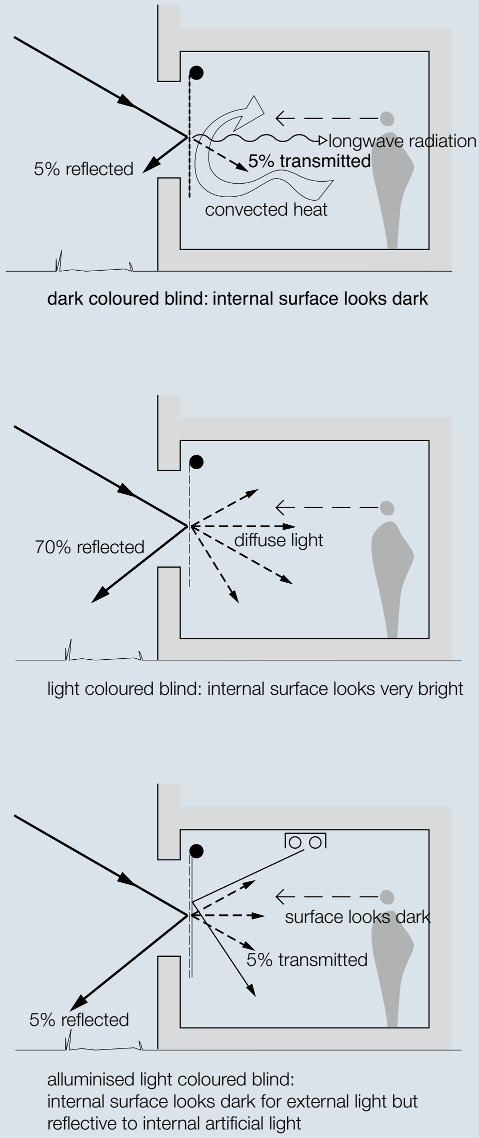
Shading type	Orientation degrees from North	View	Nat vent (in limiting conditions)	Daylight (in limiting conditions)	Seasonal response	Modulation	Notes
Overhangs							
fixed	180 +/- 30	good	good	medium	medium	none	e.g. canvas awnings +
retract	180 +/- 30	good	good	good	good	good	adjustable geometry
Louvres							
fixed	180 +/- 30	med – poor	good	medium	medium	none	View influenced by blade
adjust	all	med – poor	good	good	good	good	module size & geom.
retract.	180 +/- 30	med/good	good	good	good	medium	'good' applies to when
retract.+ adjust	all	med/good	good	good	good	good	retracted
Fins (vertical)							
fixed	90, 270 +/- 20	med – poor	good	medium	medium	none	View influenced by blade
adjust	90, 270 +/- 45	med	good	good	good	good	module size & geom.
Blinds							
retract	all	poor/good	poor	good	good	medium	'good' applies to when retracted
Screens fixed	all	poor	med - poor	poor	poor	none	not recommended

Roller blinds are another common retrofit solution due to their low cost and ease of installation. Consideration must be given to the optical properties of the fabric as indicated in figure 16.

Roller blind fabrics are optically diffusing, which means that light is re-emitted in all directions. This means that blinds of moderately high light transmission could become glare sources themselves.

When roller blinds are used in conjunction with overhangs, consideration should be given to positioning them so that they deploy upwards – i.e. with the roller at cill level. This means that sunlight striking the lower part of the window beneath the overhang will be intercepted, whilst allowing light and view through the upper part. Alternatively, the lower part of the window can be shaded separately.

With both louvre and roller blinds used internally, it must be noted that any absorbed radiation will result in heat released within the room. This means that generally blinds of high reflectance (lighter colour) will reflect a greater proportion of the unwanted visible radiation out through the glazing, thereby increasing the luminous efficacy of the system.



▲ **Figure 16**
The performance of various types of blind materials

Summary Conclusions

High Performance Daylighting is an integrated approach that takes all the functions of the window system into account. By adopting selective devices (spectral and spatial) and dynamic devices (e.g. retractable and adjustable louvers), the integrated year round energy performance can be optimised.

Recently developed high performance glazing products increase the luminous efficacy of the daylight, by transmitting less of the invisible radiation. Thus cooling loads can be reduced without increased artificial lighting energy. However, many conventional glazing products such as tinted, reflective and fritted glazing materials do not have this property.

The effective luminous efficacy the window system can be increased by improving the illuminance distribution, i.e. reducing unwanted over-illumination near the window without reducing it at the back of the room.

The time-integrated luminous efficacy can be improved by adjustable shading which responds to the prevailing sky conditions.

In most cases, large improvements can be made with glazing and shading products without necessitating major structural alterations. This makes high performance daylighting an appropriate objective for refurbishment projects.

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