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Daylight for Energy Savings and Psycho-Physiological Well-Being in Sustainable Built Environments

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Abstract

Natural light is a vital force for human beings. Successful daylighting in buildings requires trade-offs and optimization between competing design aspects (e.g. light distribution, glare, solar gains, views, etc.), whilst also including consideration of façade layout, space configuration, internal finishes and choice/operation of shading devices. However, to design energy-sustainable built environments which are conducive to human health, these variables have necessarily to be related also with biological and behavioural factors such as metabolic rhythms, psychological stimulation and occupants' preferences. Basing on a multidisciplinary review of existing literature, this paper looks at the relationship between quantitative physical measures of the luminous environment (e.g. horizontal and vertical illuminance, luminance ratio, correlated colour temperature), qualitative aspects of vision (e.g. uniformity, distribution), and psycho-physiological human response to natural light. The aim of the study consists in defining a framework to implement existing daylighting practices basing not solely on photopic requirements but also containing awareness of the demands for psychological and photobiological stimulation, so as to positively influence the health of occupants whilst enhancing energy savings.

Keywords: Daylight, Energy, Comfort, Physiology, Psychology, Health, Architecture, Sustainability

1. Introduction

The use of daylight in buildings, with its variations, its spectral composition, and the provision for external views, is of great importance for the comfort and well-being of occupants. In a workplace, for example, daylight can positively influence the health of office personnel, improving efficiency, reducing unnecessary sick leave and resulting in greater benefits for enhanced productivity. If carefully designed, a daylight strategy can also bring tangible energy savings, as long as it minimises energy use for artificial lighting and prevents glare and other visual discomfort (such as contrast, adaptation problems and internal reflections). However, the overall energy efficiency of windows depends also on thermal effects (e.g. solar gains and heat losses through glass) and their balance against heat production of artificial lighting systems.

The importance of daylight has been reflected for centuries in building legislation worldwide. Starting from the first century AD, roman laws established solar rights. British regulation (dating 1189) guaranteed that if a window had at least twenty years of uninterrupted access to daylight, that access should have become permanent ('Right of Lights'). Planning principles adopted in Boston and New York at the beginning of the 20^{th} century banned the dark street canyons emerging in urban centres and required ziggurat-shaped high-rise buildings that favoured the penetration of light at lower levels. Nowadays in Japan, regulations dictate that apartments should have at least four hours of direct access to sunlight per day. Finally, current German codes state that every workstation in a new office building must be naturally lit and placed at no more than 7.5 meters from a window (Carmody et al., 2004).

A daylight strategy has to be designed to simultaneously reflect the needs of the users and the requirements of the building, finding a balance between conflicting needs of transmission and protection. Specifying daylighting solutions for energy efficiency, comfort and well-being can however be a very complex task - often highly dependant on climate, latitude, orientation and functions - where many factors and variables can diverge from each other making selection and optimisation extremely difficult.

The task at hand for the designer is generally to identify the most appropriate properties of daylighting systems that provide adequate luminous levels and contribute to visual comfort. To do this, illuminance, luminance, colour rendering and daylight factor are commonly considered as the physical measures to be comprehensively managed. Nonetheless, in order to design energy-sustainable built environments which are also and foremost conducive to human health, these variables have necessarily to be related with qualitative and behavioural factors such as directionality of light, spectral composition of radiation, time/duration of exposure, metabolic rhythms, psychological stimulation and personal preference.

Recent findings actually suggest that visual performance and comfort can be strongly influenced by perceptive cues (such as an interesting view) other than merely by physical parameters. According to these results, it follows that psycho-physiological characters could increase the tolerance to extreme daylighting conditions beyond what is stated in international standards, thus potentially reducing the need to install and operate shading devices that could deprive internal environments of beneficial amounts of daylight and also act to the detriment of users' physiological and perceptive well-being.

In 'light' of these new findings, the aim of this study consists in defining a framework to implement existing daylighting practices basing not solely on photopic requirements for visual tasks but also containing awareness of the demands for psychological and photobiological stimulation, so as to positively influence the health and attitude of building occupants whilst also enhancing energy savings.

2. Daylight and Human Factors

2.1 Daylight in buildings

Daylight is an essential resource for life, one of the basic immutable forces of Nature, a primary element that can create meaningful and evocative architectural experiences, dictating the moods and the quality of a space. The presence of daylight in buildings should maximise the potential of architectural form while optimising human comfort and visual perception. Architecture literally depends on light, be it natural or artificial. As light reveals the forms and the spaces created within a building, it simultaneously discovers the meaning and intentions that are released through the process of conceiving and designing it, and extends its value beyond mere functional use (Guzowsky, 2000).

Daylight can reveal the experience of architecture, telling about the task to be performed, the place and the climate, marking the experience of time. Daylight is an intangible architectural tool that can underline the shapes of a building, emphasising its geometry, its spatiality, accentuating or sometimes contradicting its structure, disclosing the properties of the materials, the textures it is made of. Daylight can define and manipulate the spaces of a built environment, marking the boundary or uncovering the link between inside and outside and separating or connecting internal spaces. Daylight can be a practical and lyrical means of providing orientation, a focus, a hierarchy, encouraging movement along a path. Daylight, finally, can conceal a symbolism, a meaning which could be related to the mind or the spiritual forces of life. And yet, daylight is often considered just at one end of the spectrum of its capabilities; either solely for aesthetic purposes or solely for providing visibility for tasks. In fact, natural light should always render both these aspects and, ultimately, acquire also a further, more 'vital', importance.

Scientific research has actually widely proven the relationship existing between lighting conditions, well-being, and our very perception of the environment that surrounds us. To feel healthy, people need appropriate visual contact with the external world, the cycle of day and night, seasons, weather, etc. The species *Homo sapiens* made his appearance on Earth around 250,000 years ago and evolved under bright conditions characterised by daily (*circadian*, *circa* meaning *approximately*, and *dies* meaning *day*) and seasonal (*circannual*, *annual* meaning *year*) cycles of daylight, which dictated the times of sleep/wake periods, farming and hunting seasons, etc., while also regulating physiological and psychological functions such as heart rate, blood pressure, body temperature, emotions, etc. In other words, exposure to daylight has constantly provided the direct stimuli needed to mark the rhythm of life and contribute to feel well and healthy (Boyce et al., 2003). The life of men has always been regulated by a natural luminous rhythm: active outside during the day, and resting at night. Daylight has indeed represented, in the path of human evolution, the only realistic way of denoting basic daily moments and one of the most important means of maintaining human biological rhythms in connection to the rhythms of Nature.

Nevertheless, during the last few centuries, this natural pattern has been distorted drastically mainly as a result of societal, economic and cultural needs which have imposed a constantly increasing part of the day to be spent in confined spaces, with significant effects caused by the shift from a dynamic illuminated exterior to a static artificially-lit interior environment. The consequences of this radical change are that, in most contemporary societies, a great part of human activities is temporally organised in relation to a 'mechanical' time which is basically independent to the rhythms of our body's impulses and needs, and that is gradually moving our existences out of natural cycles and towards a global 24-hour society. In other words, we are increasingly deviating from the organic and natural pace dictated by the intensity, angle, and colour of daylight, and replacing it with an 'artificial' time which is, on the contrary, imposed by the schedule, the calendar and the clock (Van den Beld, 2001).

2.2 Non-Visual Effects of Light

Photobiology is a new stream in lighting research, revealing that there is an alternative pathway from the eye to the brain in addition to vision, which governs the complex interactions between biological functions and external stimuli (CIE, 2004). Recent medical and biological research has indeed convincingly proved that daylight, other than providing visual stimulation, has also an important non-visual effect on most of the body's biological processes (Veitch, 2005).

Boyce et al. (2003) have recognised three routes by which luminous signals interact with human functions: visual, circadian and perceptual. When light passes through the eye, its signals are carried out not only to the main visual areas but also to the parts of the brain responsible for hormonal regulation. Visible radiation hence results in stimuli involving the whole of the *physical* (energetic exchanges), *physiological* (transformation of energetic fluxes into nervous stimuli) and *psychological* (brain interpretations of those stimuli) aspects that inform the body and the mind about the characteristics of the surrounding environment and contribute to the biological metabolism of the human organism.

Other than simply providing visual information, adequate light received during the day synchronises the circadian clock, stimulating circulation, increasing the production of vitamin D, enhancing the uptake of calcium in the intestine, regulating protein metabolism, and controlling the level of hormones such as serotonin, dopamine (the 'pleasure hormone'), cortisol (the 'stress hormone') and melatonin (the 'sleep hormone', which distributes internal temporal information to the body).

For almost two centuries of ophthalmic research, the whole of these processes have been attributed to the role of only two photoreceptors in the human eye: the *cones*, active mainly in bright light conditions, and the *rods*, which regulate visual information in dim environments. As light reaches these cells, a chemical reaction occurs which determines electrical impulses to be sent via a nerve pathway to the visual cortex located in the back of the brain where these impulses are interpreted as 'vision'. However, new studies have shown that the biophysical processes that govern circadian regulation are very different from those that govern visual effects.

Berson at al. (2002) have actually detected a third cell-type of photoreceptor - which they defined as an 'intrinsically photosensitive retinal ganglion cell' (ipRGC) - which seems to be the main responsible for the regulation of biological, non-visual metabolic processes (although rods and cones probably also play a role in this respect). This new photoreceptor has been found to have its own neural connections to the pineal gland, responsible for hormone regulation, and to the suprachiasmatic nuclei (SCN) in the hypothalamus, which is the brain's internal biological clock (Figure 1). This discovery is leading towards a substantial revision of the characteristics that the luminous environment should have to sustain both the visual and the biophysical human well-being (Van Bommel, 2006).

The characteristics of the novel cell differ radically from those of cones and rods, responsible respectively for diurnal (photopic) and nocturnal (scotopic) vision. This result is extremely significant for the specification of 'healthy' lighting, especially if considering that international standards are specified basing solely on the photopic sensitivity of the human eye. As known, the light sensitivity of cones varies with the wavelength (and thus the colour) of the electromagnetic stimulus received, and reaches its maximum for green-yellow radiation corresponding to a wavelength of 555 nm. Conversely, the maximum biological sensitivity of the new photoreceptor shows a peak at about 465 nm, in the green/blue part of the visible spectrum, confirming the fact that daylight - with its variability in spectral content and the fact that, at all times, it provides a continuous spectrum with elements in all parts of the visible range - represents one of the most appropriate external forces for stimulating both vision and the synchronisation of the internal biological clock. Also the temporal resolution of the new photoreceptor seems to differ from cones and rods, since it is quite slow to react to luminous changes but then gives a continuous response after adaptation has taken place (after around 20 minutes) (Brainard et al., 2001).

In terms of the characteristics of the external stimulus, research by Aries et al. (2005) suggests that an important role in the triggering of the photobiological process is played by the vertical illuminance corrected for human anatomic restrictions, i.e. the amount of light received in the retina, although obviously the size of the pupil dictated by photopic and scotopic adaptation (and thus by cones and rods) influences sensibly the amount of light effectively entering the eye. This result implies that the vertical spatial distribution of the luminous signal is also a significant factor for biological stimulation.

The light level required for the correct functioning of the biological 'mechanisms' is yet to be systematically defined. Threshold values for the retinal illuminance are however assumed to be in the region of 1,500-2,000 lux, thus of an order of magnitude significantly higher than the recommended illuminance for most functions in common living and working indoor environments (generally ranging from 300 to 750 lux at the task corresponding to about 100-200 lux at the eye, although there is no direct proportionality between horizontal and vertical illuminance). Finally, also the dynamics of lighting in terms of intensity and spectral composition during the day seem to play an influential role for entraining bodily rhythms and the metabolic production of hormones (Aries et al., 2005).

In this regard, cortisol and melatonin play a fundamental role in regulating the level of alertness and sleep, controlling, amongst other functions, the amount of sugar in the blood and, thus, the availability of energy to 'power' human activities. Cortisol levels increase in the morning with exposure to daylight, and then, during the day, decrease gradually reaching a minimum at around midnight (Figure 2). Conversely, melatonin drops in the morning and rises at night (Van Bommel and Van Den Beld, 2004).

Obviously, a sufficient amount of retinal illumination to regulate biological processes can eventually be provided also by artificial lighting alone, although research by Boyce (2003) suggests that this is less likely to obtain the same results as natural daylight. As a matter of fact, daylight is usually the most appropriate mean to allow clear vision and simultaneously entrain the pace of the circadian rhythms, since it produces a high illuminance at the eye with a spectrum that matches both the specific sensitivity of the visual receptors and of the circadian system. Exposure to abundant natural light in the morning can synchronise the biological oscillator to the 24h rotational cycle of the Earth, thus maintaining the connection of the body's functions with the rhythm of the surrounding environment. Without regular natural light entrainment in fact, the human circadian clock would run on average on a 24h and 15-30m cycle, although differences between 'morning' (*larks*) and 'evening' (*owls*) individuals could be noticed (Van Bommel, 2006). Seasonal changes in the night-day cycle, trans-world travel, night-shift work, etc., can all affect the 'tuning' of the biological clock with the natural cycle, since the light signal received becomes asynchronous with the circadian timing (Rea et al., 2002).

In absence of normal light-dark entraining cues and appropriate exposure to daylight, the difference between the individual own 'free-running time' and the 24h cycle could result in a progressive deviation of the human biological oscillator to the rhythms of the day/night pattern, ultimately leading to a shift of the circadian pacemaker and a consequent de-synchronisation of the internal biological clock. The drawbacks of this shift could determine, also in the short and medium term, diminished sleep quality, decrease of alertness, mood changes, irritability and, ultimately, lower performances on the work place.

In summary, due to new discoveries, it becomes quite clear how daylight, other than just providing vision, orientation in space and time and environmental stimulation, can also mediate and control a large number of biochemical processes in the body, which are fundamental for human health. However, current practice for lighting design in buildings is still related to outdated visual criteria related solely to task illuminance (e.g. lux on the working plane, daylight factor, etc.) and luminance (e.g. glare). To truly enhance the sustainability of built environments - guaranteeing energy savings and fostering the health and well-being of their occupants - these criteria have to be extended to non-visual factors.

2.3 Light in the practice of design

Most people nowadays spend more than 90% of their time in confined spaces, and more often than not the lighting they are exposed to is solely regulated upon the notion that, independently from the time of day or season, the task should be accomplished efficiently and with a sufficient degree of visual comfort. Regardless of the options offered by the use of daylight, internal lighting strategies are often designed to provide luminous conditions which remain fairly constant in time, irrespective of the occupant's preferences, differences in metabolic responses and personal needs for performing their tasks.

2.3.1 International lighting standards

Most international standards specify lighting recommendations for a wide range of activities according to visual comfort criteria which are generally limited to horizontal illuminance on the task, uniformity, daylight factor, discomfort glare and colour rendering according to the activity to take place in a space. Traditional paper work to be performed on desks is generally still considered as the dominant visual design parameter, with photopic vision measures remaining the determining factors in lighting practice. Conversely, international standards do not seem to recognise, particularly for offices, the widespread evolution in computer-based activities (requiring a vertical rather than horizontal gaze), whilst they not seem to contain awareness of the requirements for photobiological stimulation and the non-visual biological effects of light. The question now is to ascertain how serious are the consequences of living and working almost exclusively in indoor spaces and often at 'unnatural' times, with much less light than outdoors and with a luminous environment fundamentally detached from biological human needs.

As an example, the European Norm for the lighting of workplaces EN 14264-1 is based upon the following visual criteria: the maintained Illuminance (E_m) - i.e. the value below which the average illuminance on the work surface is not allowed to fall - the Unified Glare Rating Limit (UGR_L) - i.e. the rate of discomfort glare - and the Colour Rendering Index (Ra) - which measures how colours appear under different light sources or when light travels through diverse media. It must be noted that the norm EN 14264-1, as most other standards, features recommendations that are expressly formulated to "enable people to perform visual task efficiently and accurately", thus not necessarily addressing "the safety and health of workers at work", although the threshold values are established also "taking into account psycho-physiological aspects such as visual comfort and well-being" (EN 12464-1, 2002).

In order to foster the visual comfort in living and working environments, whilst simultaneously reducing energy consumption and providing for the metabolic stimulation of building occupants, it is worthwhile to analyse how a 'healthy' lighting design can compensate for deficiencies in recommendations.

2.3.2 'Healthy' lighting design

Light (natural and artificial) can be described in terms of a number of characteristics which interactively regulate visual and photobiological functions: quantity, spatial distribution, spectrum, timing, duration.

In first instance, although human processes are physiologically adapted to the availability of large amounts of outdoor illumination and to significant variations in daylighting levels, interior lighting practice seems to be governed by different priorities. For example, external illuminance variations could range from over 100,000 lux on a bright summer day to a few thousands lux on a fully overcast winter day, and for periods that can fluctuate from only a couple of hours to almost 18 hours per day (this notion applies to UK latitudes). Conversely, in accordance with the standards, regardless of the source (natural or artificial) internal lighting should be set to maintain fairly constant levels at day and night and with an intensity which could be 40 to 200 times less than outside. This implies that, in most living and working places, the lighting levels required for circadian processes could not be achieved if not in areas close to the perimeter, whereas, on the other hand, daylight ingress can often be compromised by the use of shading devices due to temporal thermal or luminous discomfort.

If the criteria for lighting were changed from the current emphasis on photopic vision to photobiological demands, it follows that illuminance levels required in indoor space would need to rise significantly. Yet, if provided solely by an abundant and uncontrolled ingress of daylight, the need of high levels of vertical illuminance at the eye to stimulate biological functions (possibly up to 1,500-2,000 lux for some phases of the day) could increase the risk of thermal drawbacks such as heat losses in winter and thermal gains in summer or visual discomfort (glare, contrast). Rather, if provided by artificial installations, high illuminance at the eye could require twice as much electric lighting, and thus significantly increase energy consumptions (Veitch, 2006). Consequently, to meet at once visual and biological demands in terms of quantity and spatial distribution of the luminous stimulus, a properly designed daylighting strategy should always try to find a balance between all the various factors at play (sometimes eventually pairing with social and cultural habits, such as spending part of the day outside).

Secondly, as the spectral composition of daylight shows significant variations during the day, the photobiological entrainment would require temporal variations in the Correlated Colour Temperature (CCT) of the internal lighting. As far as visual comfort is concerned, according to the Curve of Amenity (Kruithof Diagram), the higher the overall illuminance level, the higher the CCT should be (from a perceptive point of view, high CCT under low illumination tends to make the ambient seem cold and dark, while low CCT under high lighting levels may give a rather artificial appearance to internal spaces). However, although artificial light sources are available with a spectral content similar to that of daylight on some occasions (e.g. xenon and filtered incandescent lamps), most of them are adjustable only in output levels and not in terms of CCT, and they can rarely add a significant meaning to the variability of a place (Begemann et al., 1997). Moreover, the circadian photoreceptors are mainly stimulated by short wavelengths (i.e. at around 465 nm), while artificial systems are generally designed to maximise their light output and energy efficiency according to the sensitivity of the photopic vision, which peaks in the yellow-green band (i.e. at 555 nm). Again, daylight is a luminous source whose continuous spectrum can provide for both visual comfort and photobiological functions and thus the importance of its presence in indoor living and working environments should never be underestimated.

Thirdly, daylight is highly dynamic in its intensity, spatial distribution and direction, and it seems that people strongly prefer to be kept aware of these changes, maintaining a continuous contact with the world outside and its environmental variations. Furthermore, although the receptors for metabolic regulation appear to be spread with a rather random distribution, it seems that the lower part of the retina has greater sensitivity for the entrainment of circadian processes, as it is plausible if considering that the sky tend to selectively illuminate this area rather than the upper part of the retina (Rea et al., 2002). This evidence confirms that vertical illuminance entering the eye is a key factor in 'healthy' lighting.

Finally, another aspect that lighting practices should consider in order to simultaneously enhancing the visual and physiological well-being of building occupants is concerned with the timing and the duration of exposure to light. From a visual point of view, obviously, light is needed just as long as a visual task is involved. Yet, metabolically, the timing and duration of exposure should follow the natural biological body rhythms and provide sufficient stimulation during the course of the day to avoid phase advances or delays. In general, light onset in the morning enables the biological clock to maintain synchronicity with the daily and seasonal changes in the light-dark cycle. Duration of exposure and luminous quantity are also strictly related. For example, research by Rea et al. (2002) shows that a 1h exposure to 500 lux on the work plane - a value in accordance with regulations for visual performance - is barely sufficient to stimulate the circadian photobiological system (this could be a concern for example in winter and at high latitudes, when people go and leave the workplace in the dark, and spend the day in dim interior spaces).

A further important issue not to be neglected in meeting users' comfort and well-being is the influence of colour on biological processes, a matter that may involve subjective as well as objective responses. There are reliably recordable physiological reactions to colour in addition to those associated with vision; exempla of those may be revealed by objective measurements such as galvanic skin response, electroencephalograms, heart rate, respiration rate, oxiometry, eye blink frequency and blood pressure. Whether the association between colour and physiological indexes is direct (i.e. colour stimulates the observer in such a way that the physiological response is elicited without being mediated by a cognitive intermediary response) or indirect (i.e. if exposed to a colour the observer makes certain associations) is yet to be clearly defined, also in accordance with the psychology of the individual and the influence that the perceived luminous 'message' may have on the observer's behaviour and mood (Kaiser, 1994).

In summary, the routes by which light can influence the ocular performance and the well-being of building occupants involve not only visual (quantity, spectrum and distribution of light) but also circadian and psycho-perceptual factors which take over once the luminous image has been processed. 'Healthy' lighting recommendations have thus to consider awareness of many more factors than what is currently suggested in most standards and regulations, involving, other than well-known visual comfort criteria, additional non-visual issues which are conducive for biological and psychological well-being.

3. Sustainable Visual Environments

3.1 Daylight through windows

Both visual and non-visual criteria have to be carefully applied to the design of fenestration systems to enhance energy savings in buildings (accounted nowadays for more than half of global consumptions), reduce artificial lighting demands, minimise heating and cooling loads by means of a thorough management of natural light, and meet the complex luminous and biological requirements of occupants.

Although there is no conclusive support for the notion that natural light is intrinsically superior than artificial light for stimulating visual and photobiological responses, there is absolutely no doubt that, given a choice, building occupants would prefer to live and work by daylight and to enjoy a view to the outside. Small and artificially lit spaces are often disliked, although sometimes they are accepted due to contingent factors (e.g. stringent visual tasks). Research on windowless office spaces by Boyce (2003) demonstrates that the more rooms are small and give little opportunity to relief and stimulation, the more the occupants become dissatisfied with their jobs and their physical environment. In a small room, a window may actually represent the only source of mental stimulus. Conversely, daylight and a view out may not be strictly essential if spaces are well-lit (e.g. with skylights or internal atriums) and characterised by stimulating interactive activities, as it is often the case in open spaces (social contact is a factor that could contribute to regulate the circadian system and metabolic rhythms).

Given this general preference for daylight, it is however quite hard to demonstrate that just the presence of windows for natural lighting and a view out would improve users' well-being (and thus productivity), even because people will give up daylight as long as it is associated with visual or thermal discomfort (such as glare, contrast, reflections, solar heat gain or a perceived loss of privacy) (Boyce et al., 2003).

Each visual activity demands a different relationship with the spaces surrounding it and has to meet very complex requirements, including a number of needs that reflect people's desire for a specific orientation in space and time (*genius loci*) and also aspects related to society and culture. As a matter of fact, light, both natural and artificial, plays a key-role in creating a mood and an atmosphere that should meet occupants' expectations (functions, aesthetics, ergonomics, etc.) and demands (privacy, concentration, details, etc.), whilst facilitating perception and expressing a design message of its own (Kramer, 2001).

During the day, the presence of daylight should render the spaces lively, activating and motivating in accordance with the human circadian rhythm. Daylight associated with a view should tell about the time of the day, the season, the weather. Views and variations in intensity and colour are indeed extremely stimulating for the brain and the visual apparatus, giving a contribution in terms of perceptual well-being and improving the sense of orientation and feeling of spaciousness.

A good view should normally include both the foreground and the skyline (Littlefair, 1996). Specifically, Bell and Burt (1995) have defined three 'layers' that a view out should consist of: *upper* (distant, the sky, from natural to human-made skyline); *middle* (natural or human-made objects, such as fields, trees, hills or buildings); *lower* (the foreground, including plants and paving).

The best views contain a lot of information, thus it would be preferable if a part of each layer could be seen. The lower layer is obviously particularly important since it is where people's gaze is often drawn, as it contains movement (e.g. vehicles, pedestrians, etc.) and also provides visual cues about the distance, and hence the scale, of objects in the middle layer. The shape of the opening is another important aspect. Considering that the three layers of view are stacked vertically, if the area of glazing is limited it would be generally better to have a tall, thin window rather than a short, wide opening in order to get as much information content from the view as possible. Yet, this design choice will have to be balanced with the risk of excessive thermal gains and overheating, since tall windows tend to be more exposed to high-angle summer sun, although they provide the additional advantage of bringing natural light deeper into the spaces. On the contrary, horizontal windows guarantee a better view of the external landscape. If the window is also operable, occupants will have the added option of using it for ventilation.

Other than providing psychological relief, views are also extremely beneficial to reduce muscle strain by allowing the eyes to shift from the near field surrounding the task area towards distant objects. Actually, various screen-based tasks require frequent eye movement (up to 30,000 times per day) between display, keyboard and paperwork and a limited change of focus, which in the longer term can determine fatigue, tiredness and, thus, decreased productivity. Muscular pain may add to these problems when users shift their seating position to get access to external information or avoid visual discomfort (Osterhaus, 2005).

Nevertheless, the ingress of daylight through windows can also imply major drawbacks: direct sunlight, bright clouds and reflective surfaces can cause glare, contrast and serious visual impairment. Luminance ratios in the field of view should always be contained into certain limits: too large, and it will be difficult for the eyes to adapt; too small, and there will be difficulties in estimating depths and distances.

Since people are phototropic (attracted to light), areas of high luminance in the background of the visual task should be avoided. Actually, as the eye attempts to even out the contrast between different surfaces, the ocular muscles are subject to harder and more frequent movements; tired eyes and an increased level of stress are a direct consequence. To enhance visual comfort, the task should thus normally be brighter than its immediate and general surroundings. For the ratio of luminances in the field of view of the observer, the rule of thumb 1:3:10 generally applies when users do not have immediate access to a natural light source. In case windows can be seen within the VDT area, studies suggest that the tolerable luminance ratios can be much higher, reaching up to 1:50 if the patches of bright luminance remain relatively small (around 5% of the entire field of view; Sutter et al., 2006; Newsham and Veitch, 2001).

Glare, in particular, is a serious source of visual strain that can prevent the viewer from executing his task (disability glare) or cause a significant decrease in visual performance (discomfort glare). Disability glare is generally due to a saturation effect or to a bright light source striking directly in the field of view of the observer (e.g. after-images). Conversely, discomfort glare can be associated with visual contrast and is likely to be due to the location and intensity of the light source relative to the average luminance in the eyes of the viewer. Luminance of the glare source, luminance of the background, solid angle subtended by the source to the observer's eye and the position index of the source relative to the line of sight of the viewer, are the main factors that influence the occurrence of glare, although the level of disturbance depends also on the nature of the task and on personal tolerance (Hopkinson, 1972).

Especially in modern offices, the extensive use of computer displays and visual technologies has recently caused the primary work gaze to shift from a horizontal desk surface to a vertical display screen surface. Vertical windows can thus frequently constitute glare sources (e.g. from the sky vault, the sun, reflections off surrounding buildings, high contrast of luminances), while also internal surfaces (e.g. reflective or specular finishes) or artificial lighting installations can be at the origin of the discomfort.

The occurrence and effects of glare have long been on the agenda of researchers. Disability glare has now been almost completely characterised, while the comprehension of the process linked to discomfort glare is still incomplete, especially when the visual distress is due to daylight. Actually, disability glare causes a reduction of visual performances, and it consists of an instantaneous physiological phenomenon that is likely to be quantifiable. Conversely, discomfort glare can be deemed a psychological phenomenon that is not easy to compute and predict. It consists of a non- instantaneous sensation, which does not necessarily reduce visibility in the short term and can remain unnoticed to observers, although it can cause headaches or eyestrains after long-lasting exposures (Osterhaus, 2005).

In this regards, it is worth noting that although several methods have been developed for assessment and prediction of glare from natural light - amongst others, Daylight Glare Index (Hopkinson, 1971; Chauvel et al., 1982), New Daylight Glare Index (Nazzal and Chutarat, 2001), Visual Comfort Evaluation Method (Velds, 2000), Predicted Glare Sensation (Iwata, 1998), Glare Prediction Index (Wienold and Christoffsen, 2006) - all of them appear to give higher calculated degrees of discomfort glare than those perceived under real conditions (Velds, 2002). On the other hand, more reliable glare indices developed for electric lighting systems (e.g the UGR, Unified Glare Rating; Sørensen, 1998 and CIE, 2002) cannot be applied to daylight situations. No method is currently available to assess the simultaneous impact of both daylight and artificial lighting sources on the perception of glare.

Lighting fluctuations coming from windows seem anyway to be generally more accepted than discomfort glare from artificial lamps or luminaries. This notion is consistent with the results of a number of studies (e.g. Hopkinson, 1971; Chauvel et al., 1982; Osterhaus, 2001) which also suggest that this increased tolerance to glare can be due to the natural light source being accompanied by a view. In particular, Tuaycharoen and Tregenza (2005 and 2007) have highlighted that there is less discomfort glare from a window with an interesting view than from a window of the same mean luminance but with a view of less interest. These studies substantiate previous work by Markus (1967), specifically demonstrating that less discomfort is experienced when natural scenes and multiple distance layers (e.g. foreground, middle distance, far distance and sky) are in the field of view of the observer.

The implication of these studies is that the *perceptive* effect of a subject's interest in a view can have a greater effect on comfort than the relative *objective* brightness range. It follows that if a glare source contains some information regarded as interesting, standard formulae and physical calculations are likely to overestimate the degree of visual discomfort, although it is still not clear whether this increased tolerance should be considered as a short-term effect, which may gradually disappear after prolonged viewing, or one that endures, particularly if the scene is highly dynamic. These implications could be particularly important for the design of windows especially in east/west-oriented spaces (or south orientations in winter at high latitudes), where, due to low-angle sun, discomfort glare is more likely to occur and would often suggest the design and use of obstructive shading devices.

Ongoing research by the author is investigating the complex interaction between glare, view, installation/operation of shading devices, and the effects that an excessive use of daylight protections may have on the reduction of photobiological stimulation and the energy balance of a building. Indeed, whilst an obstructive shading device is normally deployed to alleviate visual (or thermal) local discomfort, in reducing luminance in the field of view of the observer it also decreases the amount of illuminance entering the space, to the detriment of a more effective entrainment of the metabolic processes of the human body and with increased energy demands due to lower lighting levels available. In addition, by impairing (or anyway reducing) the view to the outside, obstructive daylight protections also deprive the observer of the interest, information and variation given by a contact with the outside that could have increased his tolerance to extreme lighting conditions. The consequence of this decreased tolerance is that, paradoxically, shading devices will be presumably operated more often.

The results of this continuing research are expected to provide further evidence that, when examining visual comfort, a purely physical approach can be insufficient, whereas the usefulness in practice of existing standard measures and formulae would be greatly enhanced if the inclusion of non visual-related factors improved their predictive and assessing power.

3.2 Integrated Daylight Design

3.2.1 Daylighting devices and strategies

To control the amount and distribution of natural light entering a space and to guarantee a comfortable and ‘healthy’ luminous environment, in general a good daylighting strategy should be composed of more than a simple opening in the façade (window) or on the roof (skylight). Depending on climate, orientation, functions and requirements, customised solutions or devices may need to be implemented.

Daylighting systems range from simple static (louvers, light-shelves, fixed overhangs, laser-cut panels, prismatic elements, anidolic systems, etc.) to adaptable dynamic elements (blinds, movable lamellae, advanced glazing, holographic optical elements, etc.), and/or combinations of these (IEA Task 21, 2000). The palette of devices available is very broad and numerous cutting-edge techniques are constantly being implemented in the practice of design to increase daylight penetration within indoor spaces, improve distribution and uniformity, control direct sunlight and/or reduce glare (Altomonte, 2005a).

A proper daylighting approach should always attempt to address several needs with a bespoke design, able, for example, to simultaneously provide for both, shading and deeper light penetration. In some cases, however, a thorough distinction between requirements could lead towards a differentiation of the devices to be applied, for example when addressing thermal needs (e.g. solar protection: external shading systems) or visual requirements (e.g. glare protection: internal devices).

Good daylighting strategies start from exploring simple solutions (window size, placement, self-shading, etc.) and then integrating advanced elements if required. As a matter of fact, the performances of complex and dynamic systems often depend on maintenance and durability of components, and should be adopted only in extreme situations. The positioning of shading devices for luminous and solar protection depends primarily on orientation: generally, horizontal for equator-facing façades or vertical for eastern and western openings. If internal blinds are used for visual control - as it is often the case in offices - they should preferably be composed of light, diffusive material. In terms of operational strategies, preferably each individual occupant should be able to manage his luminous environment to suit his own preference. However, it has to be considered that when blinds are closed to reduce luminous discomfort, if manual operation is the only choice human ‘inertia’ will often cause the blinds to be kept closed even after the source of disturbance has ceased (Escuyer and Fontoynont, 2002).

Proper daylight design should hence try to minimise the occurrence of the conditions under which actions aimed at reducing or eliminating the ingress of natural light arise (Boyce et al., 2003) and to develop methods whereby the actions taken to decrease or eliminate daylight penetration are reversed at the end of the day (e.g. with an automatic control of shading devices; Lee at al., 2002).

Several daylight-directing and composite shading systems have been developed to enhance daylight protection and distribution in spaces. These usually exploit the upper part of the window (clerestory) to provide light penetration deeper into the room in combination with a reflective ceiling, while the lower part of the vertical opening is often expressly designed to optimise visual performances (glare reduction) and to provide a view and a visual contact with the out of doors. For example, light shelves can be used to throw more light on the ceiling and then deeper into the spaces, delivering daylight at greater depths without significantly augmenting luminous levels near the window, whilst reducing glare in the areas close to the perimeter. Simultaneously, other than just improving the distribution of natural light, a light shelf may double as a solar protecting device, blocking direct sun when required (Figure 3).

3.2.2 Daylight-controlled artificial lighting

As far as the integration between daylight and artificial lighting is concerned, a good combination between the two can generally make it possible to gradually dim the amount of electric light required when natural illumination is sufficient for the task and for photobiological stimulation. Daylight availability, however, decreases rapidly with the distance from the window, so an adequate supplementary system is often required to balance luminous distribution.

The design of an artificial lighting system should address the requirements of both the visual task and the well-being of the occupant, allowing flexibility and personal over-ride to adjust (at least partially) the luminous environment according to personal demands. Although the option of a personal over-ride can sometimes jeopardise optimum performance in terms of energy balance, this is in general highly valued by users in terms of psychological comfort. In order to save energy and ensure at any time an optimum light distribution, a control system able to dim artificial light and/or turn luminaries off when there is sufficient daylight or after working hours may enhance best achievements and often result in minimal complaints from building occupants. Dimming control is generally easily accepted by users since changes in light levels are less abrupt and disturbing, although fully automated systems without the choice of a local personal management should preferably be avoided.

Concerning light distribution, a balanced combination of diffuse and direct light can provide recognition of three dimensional objects and liven up the environment. The lighting of an internal space should be arranged so as to guarantee an appropriate luminous ‘unevenness’ and some degree of disuniformity, thus maintaining a connection with external variations (standards normally suggest a degree of uniformity around 0.7). Daylight, in fact, is by its nature directional, so too uniformly lit environments are often disliked and do not contribute to the physiological (biorhythms) and perceptive (alertness) comfort of users. Carefully blending daylight with artificial light can, in general, ensure the best results.

In working environments, several adjustable lighting systems should be preferred to evenly distributed ceiling luminaries. Artificial ambient illumination levels should be designed to be significantly lower than task requirements, while user-controllable task lights can assure that luminous needs are met at all locations. However, if excessive glare or contrast from direct (windows) or indirect (reflections) sources is threatened, internal average luminance levels can be increased to raise adaptation levels and balance glary surfaces brightness, although this solution is likely to lead to sensible energy consumption. As a general rule, glare should preferably be counteracted directly at its source (e.g. at the window line).

To ensure adequate illumination and reduce energy consumptions, fixtures and lighting circuits should preferably be grouped by areas of similar daylight availability (e.g. in rows parallel to the window wall). It must also be noticed that artificial light usually has a mainly horizontal component, while daylight through windows, with its contribution in terms of vertical illuminance at the eye, is surely more beneficial to biological processes. To overcome these differences in directionality, suspended luminaries should be preferred to ceiling-mounted lighting systems in order to contribute to achieve non-visual stimulation, whilst providing abundant light on the task, the walls and the ceiling (Aries et al., 2002).

In terms of the correlated colour temperature (CCT) of artificial light sources for luminous stimulation, the choice should be in general determined by the function of the space, thus also involving psychological aspects such as the impression of warmth, relaxation, clarity, with other considerations. For best CCT pairing with the relatively high lighting levels required for metabolic entrainment at specific times of the day, the preferred strategy should foster the installation of lamps characterised by cooler light colours, and thus a minimum colour temperature of 4,000-5,000 K. Moreover, since in a work place both action and relaxation are needed, a dynamic artificial lighting system should also guarantee variance in both colour and lighting levels (from cool-white to warm-white) during the course of the day and according with variations in the natural light penetrating the internal environment.

Finally, regarding interior finishes, light-coloured surfaces contribute to better distribute daylight in the spaces rather than dark hues. Conversely, specular surfaces may create glare due to excessive luminance if viewed directly from a task position, while diffusive ceilings and wall-reflected daylight can increase light penetration and also facilitate the achievement of high levels of vertical illuminance for photobiological stimulation (international lighting standards generally suggest for walls a reflectance between 0.3 and 0.8, and for ceilings between 0.6 and 0.9). Furthermore, since mood can significantly be affected by the surroundings, colour monotony should be avoided as much as colour fatigue. Yet, eye-catching centres are desirable to produce a visually pleasant and mentally appealing environment.

3.2.3 Successful daylight design

A successful example of integrated daylight design is represented by the recently built City Council House 2 (CH_2) of Melbourne, the first six-Green star rated sustainable building in Australia (Note 1).

In this case, a scaffolding of plants on the northern façade (i.e. the solar-facing elevation in the Southern hemisphere) provides shading and light diffusion as well as air purification at the building openings. To decrease the risk of glare and overheating, steel trellises and external balconies - supporting vertical gardens that run the full height of the building alongside the windows - filter daylight and form a 'green' microclimate. The presence of the vines contributes to increase visual comfort for the users, both in terms of glare reduction and due to the positive psychological effect of a 'green' presence in the office areas. Light shelves, made of 50% perforated steel internally and movable fabric externally, block high-angle sun penetration during summer, while also reflecting incoming radiation deeper in the space. At the same time, internal upward-rolling retractable blinds located at the level of the light shelf, together with manually-adjustable vertically sliding timber screens at the window line, guarantee the required protection from low-angle horizontal light penetration in winter and in the late afternoon, whilst also maintaining an unrestricted view to the outside at eye level (Figure 4).

Due to the deep open plan of CH_2, natural lighting is complemented in internal areas by an artificial system designed as a two-component scheme: a background ambient lighting supplied by T5 fluorescent lamps incorporating high frequency dimmable electronic ballasts that provide a low ambient illuminance in the spaces (160 lux); and individually controlled lamps at workstations guaranteeing an additional 320 lux on each desk. In order to achieve an optimal distribution of light, materials and finishes have been chosen with an overall reflectance of 0.3 for the carpet, 0.5 for the walls, and 0.7-0.8 for the ceiling and the desktops. The lighting output is regulated by an automatic system that monitors the amount of daylight coming in the building and reflected off the light shelves and accordingly dims the electric lighting levels, thus creating a balanced mix of natural and artificial illumination. The use of workstation task lighting also creates the illusion of 'campfires' of activity which contributes to generate a rather warm and inviting atmosphere in the working spaces (Altomonte, 2005b).

A fifth of the 50M AUD overall budget of the CH_2 has been devoted to facilitate the development and implementation of sustainable principles and technologies in the design and construction process; obviously, daylighting and solar control have played a substantial role in defining the success of the strategy devised. The City Council of Melbourne has actually valued the payback period of this increase in costs in less than 10 years, with savings of more than 1M AUD per year due to reductions in energy consumption (when compared to a conventional 'green' commercial building), healthier staff, increased workplace effectiveness, and the value of a building as a guiding 'beacon' in sustainable design that is likely to influence the attitude and behaviour of its occupants (City of Melbourne, 2006).

4. Concluding Remarks

The use of daylight in buildings is commonly assumed to reduce lighting energy demands and contribute to the sustainability of built environments. However, the drawbacks normally associated with a poorly- designed and managed daylighting strategy and the energy reductions made possible by up-to-date artificial lighting systems and controls (e.g. T5 lamps with electronic ballasts), often make it difficult to justify an extensive use of daylight solely on the basis of potential energy savings (Boyce et al., 2003).

Conversely, to substantiate the choice of a daylighting strategy (particularly in commercial and tertiary buildings), it is essential to prove that such solution can simultaneously foster other significant advantages to the overall quality of the architectural space, bringing benefits to the comfort, health and well-being of the people that live and work inside the building and to the finances of organisation commissioning or occupying it (e.g. reduction in energy consumptions, increased productivity of occupants). In this regard, it must be noted that in commercial organisations salaries and benefits for employees are often of an order of magnitude up to ten times higher than building capital and operating expenses. It becomes clear that investments on the improvement of the overall quality of the working environment - such as the higher design and installation cost of bespoke daylighting systems and devices - could be easily outweighed by the financial benefits of increased satisfaction on the work place, reduction in absenteeism, turnover, and, potentially, improvement in mood, efficiency and productivity.

'Health' has been defined by the World Health Organisation as 'a state of complete physical, mental and social well-being and thus not merely as the absence of disease and infirmity' (WHO, 1946). Basing on a multidisciplinary review of existing literature, this paper has substantiated that, as a source of electromagnetic radiation, natural light is not essentially better than artificial light to ensure visual performances. However, daylight presents unique features which are proven to be conducive to human health, particularly in that it is generally available in relatively large quantities, it ensures excellent colour rendering and, simultaneously, it guarantees a variation in spectral content which represent an effective stimulation for the entrainment of the metabolic system. In addition, windows are strongly favoured in enclosed spaces also for the view out they provide, meeting the occupants' psychological needs of a continuous contact with the surrounding context, offering environmental stimuli that are beneficial for the sense of well-being, mood, concentration, motivation, etc., and potentially fostering an increased tolerance to visual discomforts such as glare, contrast or adaptation.

In summary, daylight through windows can comprehensively meet the whole of the visual, non-visual and perceptual requirements of the people living and working in built environments, clearly enlightening both the task and the internal spaces, and providing the conditions needed for health and well-being. Furthermore, if properly managed, good daylighting can contribute to reduce the energy loads for lighting and heating (solar gains) needs - and, thus, reduce the impacts of buildings on the environment - whilst concurrently creating interesting, inspiring and meaningful architecture.

Yet, when improperly delivered and regardless of its assets, daylight can increase task difficulty and cause distress that can impair the visual and perceptual comfort of users (e.g. glare, reflections, shadows, eyestrain, etc.). As an example, daylighting that provides poor visual conditions and fails to meet the occupant's needs would not only decrease performances, but may also develop frustration and alter the worker's concentration once he becomes aware of the poor level of his visual environment. In addition, an extensive use of glass for better light ingress could increase thermal losses to the outside, while an excessive penetration of daylight in confined spaces - due to an inappropriate placement and size of openings or to the lack of protections - can bring tangible solar gains, which could be regarded as beneficial in winter especially in residential buildings, but that are surely detrimental to the thermal comfort and cooling loads in summer and mid-seasons particularly in commercial built environments.

In these cases, a proper design and use of daylighting components (e.g. windows with spectrally-selective glazing) and shading devices, together with a thorough integration of daylight with artificial lighting, can optimise the balance between luminous and thermal requirements, contributing to reduce energy consumptions and increasing comfort and satisfaction for the users.

As a conclusion, when discussing daylight, the very concept of sustainability has to go beyond the exclusive optimisation of a range of energy performance factors leading to reduction of consumptions and environmental impacts, but has also to acknowledge the whole of the physical, physiological and psychological human needs. Sustainability calls for long-term changes through the interplay of several interconnected dimensions, adopting an integrated approach to architecture where a decision in one area can influence another. In this context, daylight is an intriguing aspect of design in which environmental, energetic, aesthetic, social, cultural, financial and human aspects can come together at once.

In the practice of design, hence, daylighting should not be considered as an afterthought which is taken into account only when the spatial characters of the building have already taken shape. Rather, daylight should be valued as a necessity that literally drives and directs the design of a built environment from its early stages of conception and development, dictating the quality of internal spaces and ultimately leading to buildings which are economically cheaper to run, less harmful for the environment, and, above all, healthy, inspiring and stimulating for their occupants.

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Notes

Note 1. Research on the daylighting strategies applied in the design and construction of the Council House 2 (CH_2) building in Melbourne was conducted by the author under the support of the "CH_2 Study and Outreach Program" funded by the City Council of Melbourne, Australia, in 2005.

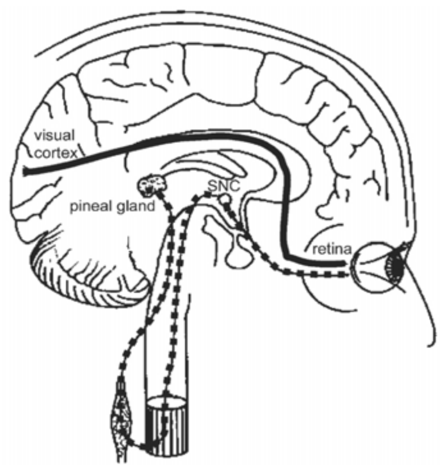

Figure 1. Visual and biological pathways from the eye to the brain

(Source: Van Bommel, 2006)

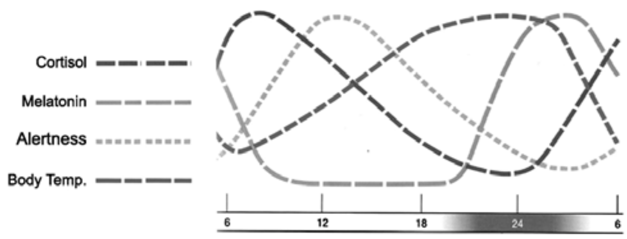

Figure 2. Daily rhythms for a 24h light/dark cycle

The Figure summarises some of the typical biological processes dictated by a regular 24h light-dark pattern, such as body temperature and the secretion of the main hormones for body regulation.

(Adapted from: Van Bommel and Van den Beld, 2004)

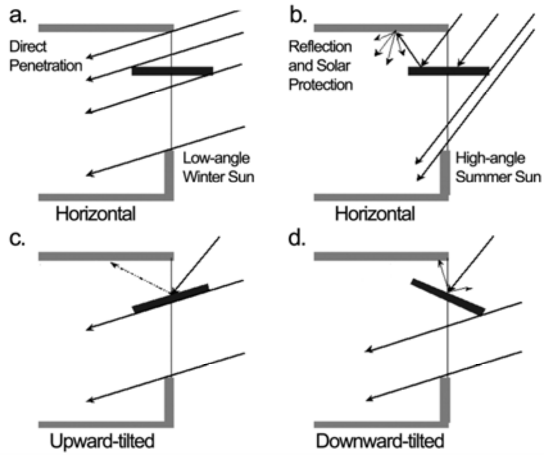

Figure 3. Exempla of Light Shelves

The Figure illustrates the functioning principles of a horizontal (a. and b.), upward- (c.) or downward-tilted (d.) light shelf in terms of solar protection and distribution of incident light.

(Adapted from: International Energy Agency, Task 21, 2000)

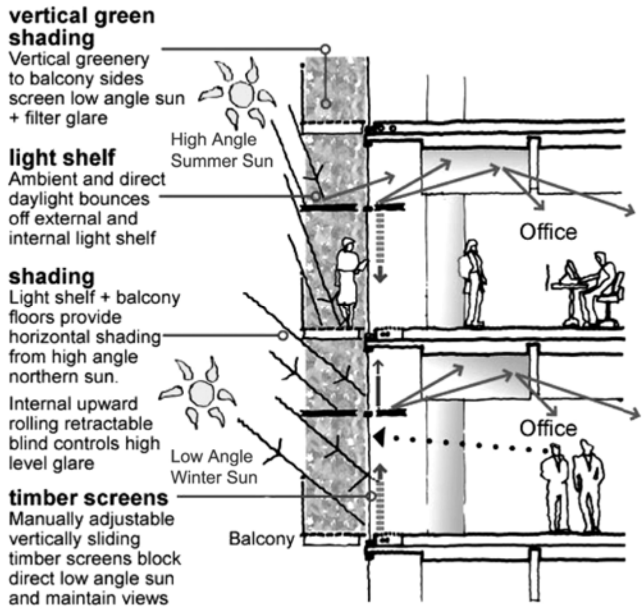

Figure 4. An example of successful daylight design

The Figure exemplifies the daylighting strategy and the use of shading and light-distributing devices applied in the North Façade (solar-facing) of the CH_2 building in Melbourne, Australia.

(Image courtesy of City Council of Melbourne; adapted)