

Daylight and the Occupant

Visual and physio-psychological well-being in built environments

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***ABSTRACT:** To substantiate an extensive use of daylight in commercial buildings it is necessary to demonstrate that, other than just providing potential energy savings, natural lighting can foster further benefits (financial, environmental and in terms of productivity) for both the owners and the occupants. Specifying daylighting solutions for energy efficiency can be a very complex task, where many factors (e.g. illuminance, glare, solar gains, views) can diverge from each other making design choices extremely difficult. Nonetheless, to foster the design of energy-conscious buildings which are also conducive to human well-being, these variables have to be related with qualitative and behavioural factors such as time/duration of exposure, directionality and spectral composition of visible radiation, psychological stimulation and user preference. Correlating literature research with lighting standards and field measurements, this paper looks at the relationship between quantitative physical factors of the luminous environment (e.g. horizontal/vertical illuminance, luminance ratio, colour temperature), qualitative aspects of vision (e.g. uniformity, distribution, contrast) and physio-psychological human response to daylighting. The aim of the study consists in defining a framework to implement existing recommendations based not only on photopic requirements for visual tasks but also containing awareness of the demands for photobiological stimulation that can influence the well-being of occupants, whilst also enhancing energy savings.*

***Keywords:** daylight, energy, physiology, psychology, well-being, sustainability*

INTRODUCTION

The presence of natural light in commercial buildings - with its fluctuations, the variations in its spectral composition, and the provision for external views - is of great importance for the comfort and well-being of occupants, potentially resulting in enhanced productivity. If carefully designed, a daylight strategy can also bring tangible energy savings, as long as it minimises energy use for artificial lighting, manages to balance heat gains and losses and prevents visual discomfort (e.g. glare).

The specification of daylighting solutions can however be a very complex task, whereas many factors and variables can diverge from each other making design choices extremely difficult. The main task for the designer generally consists in selecting the most appropriate daylighting systems and strategies that foster trade-offs between conflicting requirements of transmission and protection, and optimise *quantitative* physical measures such as illuminance, luminance, colour rendering and daylight factor to provide sufficient luminous levels and always guarantee visual comfort.

Nevertheless, if energy-conscious buildings are designed to be also conducive to human health and well-being, these variables have inevitably to be related with *qualitative* and behavioural factors such as time/duration of exposure, directionality and spectral composition of radiation, psychological stimulation and user preference. In this context, photobiology is a new stream in

daylighting research revealing the complex interactions between biological functions and external stimuli. Recent research has indeed proved that daylight, other than providing vision for tasks, has also an important non-visual effect on biological processes, synchronizing the circadian clock, stimulating circulation, controlling the level of hormones, etc. In addition, further studies suggest that visual performance and comfort can be influenced by perceptive cues (such as an interesting view) other than merely by physical parameters.

According to these findings, the routes by which daylight can affect the ocular performance and the well-being of occupants seem to involve not only *visual* but also *circadian* and *perceptual* factors which take over once the luminous image has been processed by the eye.

Lighting recommendations have thus to consider awareness of many more factors than those currently suggested in standards, involving, other than visual and energy criteria, also non-visual attributes conducive for human health and physio-psychological well-being [1].

DAYLIGHT AND WELL-BEING

Daylight is one of the basic immutable forces of Nature, a primary element that can create significant and suggestive spatial experiences [2]. Architecture literally depends on light, which reveals its forms and spaces, and simultaneously discloses the meanings and intentions

that the architect anticipated through conceiving and designing a building. Light can emphasize the experience of architecture, telling about its structure, materials, textures, the place it belongs to, the tasks to be performed in it, marking the experience of time, uncovering the link between inside and outside, providing orientation, focus, hierarchy, and increasing the significance of a building beyond functional use. And yet, light is often considered either solely for aesthetic purposes or for providing visibility for tasks. In fact, light should always render both these aspects and, ultimately, acquire also a further, biological, importance. In the path of human evolution, daylight has actually represented the only way for marking basic daily moments and one of the most important means of maintaining biological rhythms in connection to the rhythms of Nature. For millennia, all human processes have been connected with the natural daily (*circadian*) and seasonal (*circannual*) cycles of daylight, which dictated the pace of activities other than influencing metabolic functions. As a matter of fact, scientific research has recently convincingly proven the very close relationship existing between an appropriate visual contact with the luminous cycle of day and night, seasons, weather variations, etc. and healthy life conditions and physio-psychological well-being [3].

In this context, a new stream in lighting research – photobiology – reveals the existence of an alternative pathway from the eye to the brain, regulating the various interactions between biological functions and external luminous stimuli [4]. In fact, light, other than being fundamental to visual tasks has also an important non-visual effect on the body's biological processes [5]. Adequate light received during the natural day period synchronises the internal biological clock, stimulates circulation, increases the production of vitamin D, regulates protein metabolism, and controls the levels of a number of hormones such as cortisol (the 'stress hormone') and melatonin (the 'sleep hormone') [6].

Luminous stimuli thus involve the whole of the *physical* (energetic exchanges), *physiological* (transformation of energetic fluxes into nervous stimuli) and *psychological* (neural interpretations of those stimuli) functions that inform us about the surrounding environment and contribute to the functioning of the human organism.

For almost two centuries of ophthalmic research, *cones* and *rods* have been considered as the only two photoreceptor cells in the human eye. Cones are active mainly in bright light conditions (photopic vision), whilst rods regulate vision in dim environments (scotopic vision). When luminous signals reach these cells, a chemical reaction occurs which determines electrical impulses to be sent to the visual cortex located in the brain, where these impulses are interpreted as 'vision'.

However, recent studies have demonstrated that biophysical processes regulating circadian rhythms are very different from those that govern vision. Berson at al. [7] have actually detected a third cell-type of

photoreceptor – an 'intrinsically photosensitive retinal ganglion cell' (ipRGC) – which seems to be responsible for the regulation of non-visual metabolic processes.

The new photoreceptor has its own neural connections to the pineal gland, responsible for hormone regulation, and to the Suprachiasmatic Nuclei (SCN) in the hypothalamus, the brain's biological clock (Fig. 1).

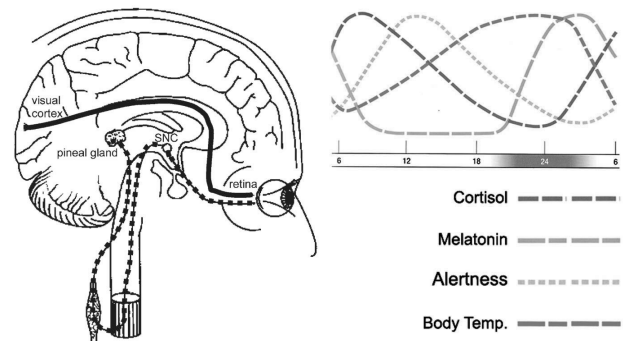


Figure 1: Visual and biological pathways from the eye to the brain and daily rhythms (Source: Van Bommel, 2006)

Since the sensitivity of this new photoreceptor differs radically from that of cones and rods, this discovery is extremely significant for the specification of a 'healthy' luminous environment able to sustain both the visual and the metabolic well-being of individuals, although most of the international lighting standards are still specified basing solely on the characters of photopic vision [8].

The light sensitivity of cones varies with the wavelength (and thus the colour) of the luminous signal, and reaches its maximum at 555 nm (green-yellow light). Conversely, the sensitivity of the new photoreceptor shows a peak at about 465 nm, in the green/blue part of the spectrum. Also the temporal resolution of the new photoreceptor is quite peculiar, since it is slow to react to luminous changes but then gives a continuous response after adaptation has taken place (around 20 minutes) [9].

In terms of the luminous stimulus, an important role in the triggering of the photobiological processes seems to be played by the vertical illuminance received by the eye corrected for anatomic restrictions, i.e. the light received in the retina [10]. In fact, although the receptors for metabolic regulation appear to be randomly dispersed in the eye, the lower part of the retina shows greater sensitivity for the entrainment of circadian processes, as it is plausible considering that the sky tends to illuminate this area rather than the upper part of the retina.

Threshold values for the retinal illuminance are assumed to be around 1,500-2,000 lux, thus of an order of magnitude significantly higher than the recommended illuminance on the working plane for most tasks (300-500 lux). This result implies that the vertical spatial distribution of the luminous signal is a significant factor for biological stimulation. Finally, also the dynamics of lighting in terms of intensity, spectral composition and direction during the day seem to play an influential role.

Obviously, sufficient retinal illumination to entrain biological processes could eventually be provided by artificial lighting, although this solution is less likely to obtain the same results of daylight in terms of combined visual comfort and bio-regulation, since natural light usually produces a high illuminance at the eye with a spectrum that matches its circadian sensitivity [11].

Daylight, with its variability in spectral content and the fact that, at all times, it provides signals in all parts of the visible range, thus represents the most appropriate stimulus for vision and the concurrent regulation of the biological clock. In particular, morning light plays an essential significance in the synchronisation of metabolic rhythms to the 24h rotational cycle of the Earth. Without regular daylight entrainment, in fact, the human circadian clock (*circa* meaning approximately, and *dies* meaning day) would run, on average, on a 24h and 15-30m cycle, ultimately leading to a shift of the circadian pacemaker and a de-synchronisation of the biological clock [12].

In summary, due to new discoveries, it becomes clear how natural light, other than just providing visibility for tasks, orientation in space and time and environmental stimulation, can also mediate and control a large number of biochemical processes in the human body, which are fundamental for health and well-being. Yet, current practice for lighting design in buildings is still based on outdated visual criteria related solely to horizontal task illuminance and luminance in the field of view (e.g. glare). Conversely, to foster the health of occupants and truly enhance the sustainability of built environments, these criteria have to be extended to non-visual demands.

‘HEALTHY’ DAYLIGHTING CRITERIA

Nowadays people spend more than 90% of their time indoors – often in offices – and in all cases the lighting strategy is uniquely based upon the notion that, whatever the time of day or the season, the tasks have to be performed efficiently and with an adequate level of visual comfort. Yet, despite the options offered by daylight, internal lighting is often designed to provide fairly constant luminous conditions at all times, irrespective of the occupants’ preferences, differences in metabolic requirements and needs for individual tasks.

As a matter of fact, regardless of the widespread use of computer-based activities in offices (which require a vertical gaze), traditional paperwork to be performed on desks is still considered as the prevailing visual design parameter, with photopic vision remaining the key factor in lighting regulations. Actually, most international lighting standards – as the European Norm EN 12464-1 – specify recommendations for a wide range of activities according solely to visual comfort criteria, such as the maintained illuminance on the work surface (E_m) – i.e. the value below which the horizontal illuminance is not allowed to fall – the unified glare rating limit (UGR_L) – i.e. the rate of discomfort glare (although this can be

calculated with a certain degree of certainty only for luminaries) – and the colour rendering index (R_a) [13].

On the contrary, awareness of the requirements for photobiological stimulation (e.g. vertical illuminance, spectral composition of light, duration of exposure, etc.) is generally ignored. The question now is to establish how serious are the consequences of working and living with much less light than outdoors and with a luminous environment fundamentally detached from biological needs, and how this can be compensated by a ‘healthy’ lighting design able to, at once, meet visual requirements, reduce energy consumptions and guarantee a correct metabolic stimulation for occupants.

Light can be described in terms of a number of factors that govern visual and photobiological functions: quantity, spectrum, spatial distribution, timing, duration.

In first instance, it must be considered that all human processes are physiologically adapted to the availability of large amounts of outdoor illuminance (up to 100,000 lux on a sunny day) and to significant daily and seasonal variations in daylight levels. Conversely, according to the standards, internal lighting is often set to fairly constant levels at day and night and with an intensity which could be 40 to 200 times smaller than outside. This implies that, in most working places, the lighting levels required for circadian processes can not be achieved if not in areas close to the perimeter, where, on the other hand, daylight ingress can be compromised by competing thermal needs. Yet, if criteria for lighting were to be modified basing on photobiological demands, it would follow that illuminance levels required in indoor spaces would need to rise significantly, at least for some phases of the day. However, if this increased vertical illuminance to stimulate biological functions was to be provided by daylight alone, the risk of solar gains, thermal losses or potential visual discomfort (glare) would obviously be considerably higher [14]. Rather, if provided solely by artificial lighting, higher illuminance at the eye would imply increased energy needs. As a consequence, a thoroughly-designed daylight strategy has always to find a balance between all the factors at play (sometimes compensating its deficiencies with flexible social and cultural habits, such as spending part of the day outside!). Secondly, just as the spectral composition of daylight shows large variations throughout the day and seasons, a suitable photobiological entrainment would require temporal variations in the correlated colour temperature (CCT) of the lighting stimulus. As far as visual comfort is concerned, according to the Kruithof Diagram the higher the illuminance, the higher the CCT should be. However, although artificial light sources are available with a spectral content similar to that of daylight on some occasions (e.g. xenon incandescent lamps), most of them are adjustable only in output levels and not in CCT. Moreover, it must be considered that circadian photoreceptors seem to be mainly stimulated by short wavelengths, while luminaries are generally designed to

maximise their energy output according to the photopic visual sensitivity, which peaks in the yellow-green band. Thirdly, natural light is highly dynamic in its intensity, spatial distribution and direction, and it seems that people would strongly prefer to be kept aware of these changes. Another aspect that lighting standards should consider is concerned with the timing and the duration of exposure. From the point of view of vision, light is needed just as long as a visual task is involved. Yet, metabolically, the timing and duration of exposure should follow the biological rhythms of the body and provide sufficient stimulation during the course of the day to avoid phase advances or delays. Duration of exposure and luminous quantity are also strictly related. For example, abundant light onset in the morning enables the biological clock to maintain synchronicity with the changes in the light-dark cycle (this could be a concern in winter, when people go to work in the dark, and spend the day in interiors whose illumination is based solely on photopic criteria).

A further important issue not to be neglected is the influence of colour on biological processes, a matter that may involve objective as well as subjective responses (e.g. heart rate, respiration rate, oximetry, eye blink frequency, etc.). Whether the association between colour and physiological indexes is *direct* (i.e. the response is elicited without being mediated by a cognitive intermediary reaction) or *indirect* (i.e. exposed to a colour the observer makes certain associations) is yet to be defined and involves also psychological issues [15].

Finally, in terms of the integration between natural and artificial lighting, a good combination can generally make it possible to dim the amount of electric light when daylight is sufficient. If an automatic dimming system is used, a personal over-ride is in general highly valued in terms of perceptive comfort, although it can sometimes jeopardise optimum energy performance. It must also be noted that artificial lighting usually has a mainly horizontal component, while daylight through windows, with its vertical illuminance, is surely more beneficial to biological processes. Suspended luminaires should thus be favoured for non-visual stimulation, while also providing copious light on the task and the ceiling.

In summary, photobiological research leads to the hypothesis that healthy lighting is influenced by many more factors than what is suggested in most standard and regulations, involving, other than well-known visual comfort criteria, additional non-visual factors which can influence the ocular performance as much as the physiological well-being of building occupants.

PERCEPTION AND PSYCHOLOGY

To further support the notion that daylight is generally superior than artificial lighting for stimulating, at once, visual and photobiological responses, there is no doubt that, given a choice, building occupants would prefer to live by daylight and enjoy a view out. However, despite

this general preference for natural light, it is hard to demonstrate that just the presence of windows would improve users' comfort, well-being and productivity, even because people will swiftly give up daylight if it is associated with visual or thermal discomfort [11].

Each visual task demands a specific relationship with the environmental factors surrounding it and has to meet complex needs that reflect people's desire for orientation in space and time (*genius loci*), expectations (functions, aesthetics, ergonomics, privacy, concentration, details, etc.), and also aspects related to society and culture.

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, and improve the sense of orientation and feeling of spaciousness. In addition, views out 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.

A good view should preferably include three 'layers': *upper* (distant, the sky – from natural to human-made skyline); *middle* (natural or human-made objects, such as trees, hills or buildings); and *lower* (the foreground, including plants and paving) [16]. Since these three layers are stacked vertically, if the area of glazing is limited (e.g. for thermal needs) 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. Conversely, horizontal windows guarantee a better view of the landscape.

Nevertheless, daylight through windows can also imply major drawbacks. As previously noted, in modern offices the extensive use of computer displays has caused the primary work gaze to shift from a horizontal desk plane to a vertical display screen surface. Vertical windows can thus frequently constitute glare sources (e.g. from the sky vault, bright clouds, the sun, reflections off surrounding buildings, etc.), although also internal reflective surfaces or artificial lights can be at the origin of the distress. Luminance ratios in the field of view should always be contained within certain limits: too large, and it will be difficult for the eyes to adapt; too small, and depths and distances will be hard to estimate. The visual task should normally be brighter than its immediate and general surroundings. To this aim, the rule of thumb 1:3:10 generally applies, although, in case windows can be seen within the VDT area, studies suggest that the tolerable luminance ratio can be much higher, reaching up to 1:50 if the patches of bright natural luminance are small [17].

Glare is a serious source of visual strain that can prevent the viewer from executing his task (*disability glare*) or cause a decrease in 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 normally linked to the location and intensity of the light source relative to the average luminance in the eyes of the viewer, although the disturbance depends also on the nature of the task and on personal tolerance [18].

The full comprehension of the process linked to discomfort glare is however still incomplete, especially when the visual strain is linked to daylight [19]. Lighting fluctuations coming from windows seem anyway to be generally more easily accepted than glare from artificial luminaires. This notion is consistent with the results of a number of studies [20], which also suggest that an increased tolerance to glare can be due to the natural light source being accompanied by a view. In particular, recent research has 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, specifically when natural scenes and multiple distance layers are observed [21].

The implication of these studies could be that the perceptive *subjective* effect of the interest in a view can have a greater effect on perceived comfort than the relative *objective* brightness range. It follows that if a glare source contains some information regarded as interesting, standard formulae and calculations are likely to overestimate the degree of visual discomfort, even if it is still unclear whether this increased tolerance should be considered as a short-term effect or one that lasts [22].

In any case, these results provide further evidence that, when examining visual comfort and well-being, a purely physical approach can be insufficient. Consideration of non-visual factors, on the other hand, can be particularly important for the design of windows in situations where, due to low-angle sun, discomfort glare is likely to occur and would suggest the design and use of shading devices. The use of obstructive blinds, in fact, by reducing the luminance in the field of view of the observer, would also decrease the amount of available illuminance, to the detriment of metabolic processes and with increased energy demands. In addition, by impairing visual contact with the outside, shading devices would also deprive the observer of the interest, information and variation given by a view that could have increased his tolerance to extreme lighting conditions and discomfort glare.

MEASUREMENTS AND OCCUPANTS' SURVEYS

Field measurements linked to occupants' surveys are a fundamental mean to relate physical quantities to psychophysiological human response to environmental stimuli. A pilot daylight testing was performed to these aims at the Council House 1 (CH₁) offices in Melbourne, Australia, as part of a comprehensive Post-Occupancy Evaluation campaign set by the City Council to benchmark the building's energy performance and users' comfort before moving to the newly built Council House 2 (CH₂), the first building in Australia to receive a 6-Green Star rating for excellence in sustainability [23].

CH₁ comprises a typical open plan layout fitted with conventional partitioning and furniture, overhead recessed fluorescent luminaires and task lighting. Most of the office desks have direct access to daylight and a view out. The windows are mostly non-operable and are equipped with adjustable internal blinds for light control. The daylight testing consisted of measurements taken at regular intervals at selected locations. Surface area luminance (cd/m^2) was measured with a calibrated Nikon Coolpix 5400 camera equipped with a fish-eye lens to characterise the luminance homogeneity or non-homogeneity in the field of vision of the occupants, and then processed via the software Photolux 1.3.5 (ENTPE). Concurrently, horizontal and vertical illuminance and correlated colour temperature of the light sources were measured to fully characterise the visual environment. The figure below provides an observed example of a workplace that exhibits potential glare problems (Fig. 2).

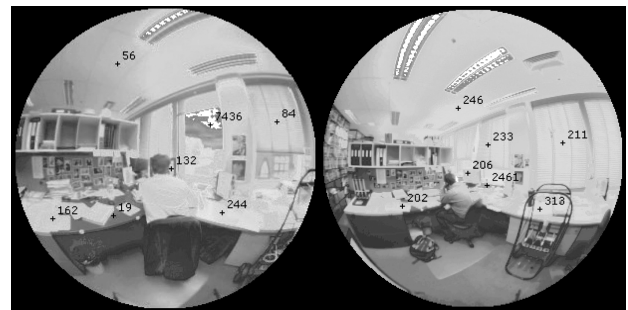


Figure 2: Luminance measurements (in cd/m^2) taken at 10 am during winter (left) and summer (right)

The testing was performed in two seasons, winter and summer, at the same time of the day (10am), in an easterly-oriented work station. In the winter testing, it is evident how the low-angle sun potentially creates risks of glare in the field of vision of the occupant. The luminance ratio between the window ($7,436 \text{ cd/m}^2$) and the Video Display Terminal (132 cd/m^2) is actually 1:56, a value which clearly flags probable discomfort glare. Yet, the venetian blind is not drawn by the user to counteract this visual annoyance. As a matter of fact, upon interview the occupant revealed his awareness of glare but reported his preference to mainly concentrate on file processing and paper-work rather than screen-based tasks in the early hours of the morning, in order to benefit of a bright environment and a view out for waking up and feeling better for the rest of the day. Conversely, the measured conditions were well-suited to paper-work tasks as per current standards. Actually, at the time of testing the horizontal illuminance on the work plane was 1,600 lux, while the CCT was slightly above 5,000 K (mainly coming from daylight), and thus in the comfort area also according to the Kruithof Diagram.

During summer months a different situation applies. Paradoxically, although the sun has a higher course and path in the sky – and thus does not necessarily constitute

a source of direct glare – the blind here has been drawn by the user to reduce the brightness of the window and its contrast with his visual task. The resulting luminance ratio between the visible part of the sky ($2,461 \text{ cd/m}^2$) and the VDT area (206 cd/m^2) is around 1:11, and thus within the limits conventionally suggested by lighting practices. Yet, the decrease in luminance ratio due to the use of the blind also results in lower visual and luminous stimulation for the occupant. This choice may be due to the fact that the user had already benefited of sufficient exposure to daylight – and thus metabolic and psychological stimulation – on its way to work, and thus did not require high level of illumination to feel better. Because of the blind, also illuminance on the work plane was much lower than the winter measurement (600 lux) – yet sufficient for the task – while CCT was around $4,000 \text{ K}$ (i.e. mainly due to the cool-white fluorescent lamps). The measured conditions are still within the standard and the comfort band of the Kruithof Diagram, although they significantly rely on the use of artificial lighting sources. This is a clear example of how physio-psychological factors can influence and eventually compensate physical luminous discomfort to the benefit of the user (well-being) and the organisation (productivity and energy savings), although, in the measured building, the absence of a light sensor able to dim or turn off artificial lights in presence of sufficient daylight prevents this saving.

CONCLUSION

Basing on the literature and on field measurements, this paper has substantiated that, other than providing potential energy savings, daylight can foster significant advantages to the quality of architectural spaces, bringing benefits to the health of people that live in buildings, and to the finances of the organisations commissioning them. As a source of electromagnetic radiation, natural light is not intrinsically better than artificial light to ensure visual performances. However, daylight is endowed with unique features which are conducive to human health, as it is generally delivered in large quantities and ensures a continuous variation in spectral content, thus presenting an effective stimulation for the human circadian system. In addition, windows are favoured also for the view out they provide, meeting the occupants' psychological needs of a continuous contact with the surrounding context (biophilia) and offering environmental stimuli that are beneficial for the well-being, attitude, mood, concentration, and, possibly, productivity of occupants. 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 a building have already been formulated. Rather, daylight should be valued as a necessity that drives and directs the design from its early stages, ultimately leading to better architecture which is cheaper to run, less harmful for the environment, and healthy and stimulating for its users.

ACKNOWLEDGEMENTS. Research for this paper was initiated under the support of the Melbourne City Council. Daylight testing was conducted in collaboration with the MABEL (Mobile Architecture and Built Environment) Laboratory, Deakin University, Australia.

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