WHAT WE KNOW ABOUT WINDOWS AND WELL-BEING, AND WHAT WE NEED TO KNOW

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Abstract

Our common experience is that windows are desirable; in recent years science has begun to explain why. The last reviews of this literature were published a decade ago; therefore, we felt the time to be right for a comprehensive review and for the development of a research agenda to move activity forward in directions that would have practical applications. The review identified three broad processes through which residential windows and skylights can affect people in their homes, for good and ill: visual processes, acting primarily through light detected at the retina by rods and cones; non-visual ocular processes, acting primarily through light detected at the retina by intrinsically photoreceptive retinal ganglion cells; and processes occurring in the skin. This qualitative review revealed that there is no shortage of research questions facing photobiologists, psychologists, architects, lighting designers and others in the broad lighting community.

Keywords: Windows, daylight, view, health, well-being, intrinsically photoreceptive retinal ganglion cell, visual performance, spatial appearance, comfort

1 Introduction

Interest in using light to the benefit of building occupants through daylighting and lighting design has never been higher. Scientific advances such as the discovery that intrinsically photoreceptive retinal ganglion cells (ipRGCs) are responsible for entraining circadian rhythms to patterns of light and dark, and furthermore that those cells are most sensitive to short-wavelength optical radiation, led the CIE in 2004 to promulgate five "principles of healthy lighting" [CIE 2004/2009]. The same report also suggested that these principles should lead to a renewed emphasis on architectural daylighting. Daylight is rich in that area of the spectrum and bright at the times of day that seem most important to these processes.

The science has moved rapidly in the ten years since the last substantive reviews of the state of the art on the health and well-being effects of daylight and windows [Boyce et al. 2003; CIE 2004/2009], making it time for a renewed examination of the literature. We recently reviewed this literature with a focus on residential buildings [Veitch and Galasiu 2012], but in the process identified much that applies to any building type. This conference paper will focus on what is known generally about the effects of windows on human well-being and will conclude with a set of general research questions that, as yet, have no conclusive answer.

2 Research Summary

The literature review revealed that there are three broad pathways through which electromagnetic radiation from the near UV through the near infrared regions influence human health and well-being. These are visual and non-visual ocular processes mediated by the retina and processes through the skin; skin processes include thermal effects. Figure 1 shows a schematic diagram of the two ocular pathways as they are currently understood. This section provides a very brief introduction to these processes; for more detail see Veitch and Galasiu [2012].

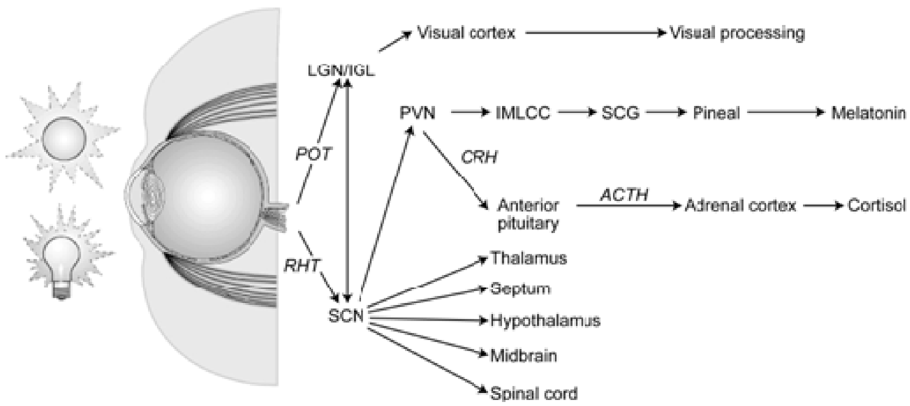

Figure 1 – Pathways from eye to brain (CIE, 2004/2009). Schematic diagram of two eye-brain pathways. Light received by the eye is converted to neural signals that pass via the optic nerve to these visual and non-visual pathways. POT = Primary optic tract. RHT = Retino-hypothalamic tract. LGN/IGL = Lateral geniculate nucleus / Intergeniculate leaflet. SCN = Suprachiasmatic nucleus of the hypothalamus. PVN = Paraventricular nucleus of the hypothalamus. IMLCC = Intermediolateral cell column of the spinal cord. SCG = Superior cervical ganglion. CRH = Corticotropic releasing hormone. ACTH = adrenocorticotropic hormone. © 2009, CIE. Used by permission.

2.1 Visual Processes

2.1.1 Visual Performance

Windows admit light that we use to see tasks using visual processing. Visual performance is very well understood to be determined by task contrast, task size, and retinal illuminance, but moderated by ocular health and age. Vision science uses strong research methods that have led to predictive models for achromatic tasks performed at photopic luminance levels [Rea and Ouellette 1991]. Chromatic tasks, however, are less well understood by visual performance models [Boyce 2011].

2.1.2 Spatial Appearance

Windows contribute to spatial appearance. Spaces with windows are generally preferred over those without. If one considers a wall to create a boundary, windows and skylights make the boundary permeable by providing a view to the world beyond (Figure 2); this combination of prospect (through the window) and refuge (within the wall) is pleasing [Stamps 2010]. Although the research designs used to study these effects are strong, there is too little specificity from which to derive design guidance concerning window sizes or shapes. Furthermore, there is some evidence that desires for privacy in different room types influence window preferences and that these might also vary across cultures [Lau et al. 2010].

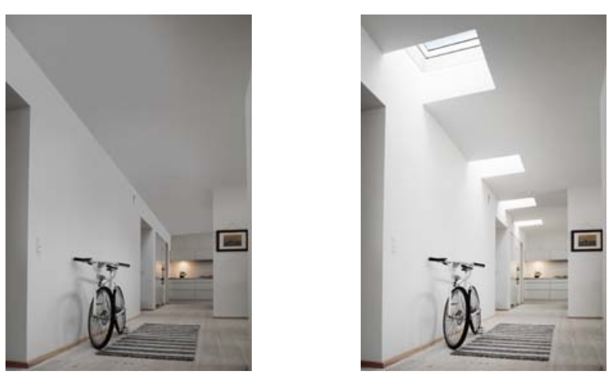

Figure 2 – Windows and skylights move the room boundary from the wall or ceiling to the distance, creating a permeable boundary. Photo © VELUX A/S. Used by permission.

2.1.3 Visual Comfort

Sunlight provision provides light and warmth; in homes and in some non-domestic buildings this is sometimes seen as therapeutic. Sunlight nonetheless needs to be linked to appropriate controls to minimize possible thermal and/or visual discomfort to the occupant (Figure 3). The degree of visual discomfort can be predicted in part by vertical eye illuminance, glare source luminance, solid angle and position [Wienold and Christoffersen 2006]; however there is some evidence that task focus, the glare source being sunlight, and the quality of the exterior view, might moderate the experience [Osterhaus and Bailey 1992]. Data concerning how individuals use shading devices to prevent discomfort is inconclusive.

Figure 3 – Direct sunlight requires controls to limit thermal and visual discomfort. Photo © VELUX A/S. Used by permission.

2.1.4 Stress and Restoration

Windows also promote restoration following stressful experiences by providing a view of outdoors (Figure 4) [Hartig et al. 1991; Ulrich 1984]. Most of this research has focused on a nature view, but there is limited evidence that the quality of the view also plays a role [Ariës et al. 2010]. An attractive view, whether of a built or natural scene, might promote cognitive, affective, and physiological restoration. Of these three forms of restoration, the cognitive effects are best understood; the opportunity to relax attentional focus by visually exploring a nature view restores depleted capacity [Berman et al. 2008].

Figure 4 – A view of nature, especially if it is attractive, can promote physical and mental restoration. Photo credit: Clemow Ave. Residence Architect: John Donkin Photo © Peter Fritz. Used by permission.

2.2 Non-Visual Ocular Processes

2.2.1 Circadian Regulation

Turning to the non-visual processes that are mediated by retinal photoreception, we see that since the 2004 CIE report 158, it has become clearer that there are at least two channels: one for circadian regulation, and one regulating mood and alertness [Cajochen 2007]. The path from the ipRGCs to the suprachiasmatic nucleus of the hypothalamus takes information about irradiance to the brain centres that govern circadian rhythms (Figure 1). We anticipate seeing the first consensus statement concerning the action spectrum of the ipRGCs in the coming months, following an expert workshop held in January 2013. The original observation of CIE 158:2004/2009, that daylight – through windows or outdoors – could be a good source of short-wavelength and bright daytime light exposure to regulate circadian rhythms, stands.

What is not yet clearly established is the optimal pattern of light exposure to best entrain circadian rhythms in a specific climate. The fact that humans have lived for centuries at latitudes from the extremes of north and south to the equator demonstrates that adaptation to widely varying light and dark rhythms is possible. However, it is possible that some patterns of light exposure and ways of life leave one in better physical and mental health than others.

2.2.2 Mood and Alertness

The realization that mood and alertness might operate according to a separate pathway is comparatively new. Limited evidence, but consistent across methodologies, suggests that acute bright light exposure by day can influence serotonin metabolism [aan het Rot et al. 2008], leading to improved mood and more cooperative social behaviours [aan het Rot et al. 2007]. The spectral sensitivity function of these effects is not known. Windows, of course, remain an excellent source of this bright light exposure.

2.3 Skin Processes

Windows also expose skin to radiation at both the ultraviolet and infrared ends of the spectrum. Heat transfer can predict the thermal effects of windows based on the window properties and the environmental conditions on both sides, and models such as Fanger's Predicted Mean Vote (PMV) [Fanger 1970] can be applied to the physical data~~e~~ to predict occupants' thermal sensation. The PMV model, however, does not take into account human adaptability [Brager and de Dear ; de Dear 2004]. Moreover, it has become apparent that some thermal conditions are acceptable in some circumstances but not in others, a phenomenon that de Dear [2011] has labelled "alliesthesia". de Dear proposed a model of thermal perception that accounts for this phenomenon, but even his model does not include the possibility that this perception might differ for office environments (which practitioners are most concerned about) and homes, nor that individual differences such as age, sex, and task involvement (as opposed to physical activity, which is accepted as an influence on thermal comfort and is a factor in the PMV model) might also be influential.

On the ultraviolet (UV) end of the spectrum, questions remain about the necessary UV dose to promote vitamin D metabolism, but there are no questions concerning whether windows should be designed to deliver this dose: The risks to materials and individuals are too great to use windows in this way [Juzeniene et al. 2011; Webb 2006].

3 Research Agenda

Based on the extensive literature review in the original report [Veitch and Galasiu 2012], we developed a research agenda. The original report included research questions specifically focused on residential buildings and questions that apply more generally. Here we present only the questions that are generally applicable, and only the material specifically related to the health and well-being effects, leaving out energy considerations, other building science issues, and building regulations. Detailed citations for this material are available in the original report.

Table 1 – Research Agenda for Effects of Light Through Windows

Section	General findings	Strength of information	Open Questions
2.1.1 Visual performance	• Visibility is governed by task contrast, task size, retinal illuminance, and moderated by age	• Vision science evidence uses strong research methods. There are few open questions	• Visual performance models do not address chromatic tasks.

Section	General findings	Strength of information	Open Questions
	and visual health • Spectral influences on acuity might favour daylight as a source. • Stray light can reduce visibility, especially a problem for older people.	about achromatic visual performance at photopic levels. • Age-related reductions in visibility because of glare can be predicted well.	• There is limited data for people with low vision.
2.1.2 Spatial Appearance	• Windows make most spaces appear more pleasant, and are generally preferred over windowless spaces. • Permeability theory predicts that spaciousness and safety needs jointly influence preferences for boundary openings, including windows. • Limited data from offices leads to recommended window sizes.	• Research designs are generally good, particularly for tests of permeability theory. • However, there is too little data on specific dimensions or window features to create design guidelines based on spatial appearance models.	• Further investigations of desired degrees of boundary roughness for rooms of various types would help to move from the theoretical level to applications; these studies should use stimuli with greater ecological validity. • Does the view beyond the boundary influence spaciousness judgements?
2.1.3 Visual comfort	• Unwanted high luminances in the eye can cause discomfort. For large uniform electric sources in offices the discomfort is predictable from the source luminance, adaptation luminance, location and size of the source. • For daylight in offices, discomfort can be predicted from vertical eye illuminance, glare source luminance, solid angle and position (DGP). • Discomfort is also a function of the light source, task involvement, and for windows, of the	• All discomfort prediction models have limitations and are considered problematic, particularly given the poor predictive power for nonuniform light sources. • Daylight and electric lighting models have not been integrated, and no model accounts for the influence of non-lighting variables.	• No physiological or psychological mechanism accounts for the experience of visual discomfort. • There is no consistent data concerning the experience of discomfort as a function of age or other demographic characteristics. • New models are needed to account for discomfort associated with large arrays of small sources (e.g., LEDs), and to integrate across light sources (electric and daylight).

Section	General findings	Strength of information	Open Questions
	nature and quality of the view. • There is limited data concerning the use of shading devices in offices to prevent discomfort.		
2.1.4 Stress and restoration	• Access to nature through images, window views, and nature experiences improves well-being through physiological calming, improved attention focus, and improved mood and satisfaction. • An attractive view (whether natural or not) might also be restorative.	• This topic shows strong research designs and consistent results across methodologies.	• Cognitive benefits can be explained by attention restoration theory, but there is more to learn about the mechanisms underlying the physiological and affective responses.
2.2.1 Circadian regulation	• ipRGCs are the principal light/dark detectors for circadian regulation and pupil size. Rods and cones have influence, but exactly how is poorly understood as yet. • Circadian regulation by light is influenced by the spectrum, intensity, duration, timing and pattern of light exposure. • Periods of both light and dark exposure each day are needed for circadian entrainment. • Increased exposure to short-wavelength light (including daylight) is an efficient way to increase light exposure for circadian entrainment, but other wavelengths also contribute.	• The fundamental photobiology evidence for the novel photoreceptor system is strong, but there remain many gaps in knowledge. • Many investigators do not report the light exposure with the correct units or details necessary to calculate the light exposure or light dose, making it impossible to compare results. • Ecological measurements of wrist illuminance provide limited means to study exposures accurately. • There is no standard definition of a healthy circadian rhythm (or range of patterns) in terms of the amplitude, duration, or timing of melatonin secretion	• Exactly what is the action spectrum for circadian regulation? Furthermore, does exposure to polychromatic light follow the same curve as the monochromatically-derived ones? • What are the interactions between the pattern-detecting (visual) and irradiance-detecting (non-visual) photoreceptors at both the retinal and brain levels? • How dark does the dark period need to be, in counterpoint to the light exposure?

Section	General findings	Strength of information	Open Questions
		nor of sleep/wake patterns. This makes it difficult to establish the practical significance of statistically significant results.	
2.2.2 Mood and alertness	• Light exposure influences mood and alertness independent of its influence on circadian regulation. Higher daytime light exposures result in more positive mood, less pain, and smoother social interactions. • The effects do not show the same spectral response as melatonin suppression (i.e., both long and short wavelengths have this influence). • Effects on mood appear to be mediated by an influence on the neurotransmitter serotonin.	• This area is new, and findings are limited. Replication studies are needed, particularly for the effects of light exposure on social behaviour.	• What is (or are) the mechanism(s) underlying the acute alerting effects of light, by day or night? What spectral sensitivity function predicts these effects? What is the dose-response function for this system? • What is the mechanism by which light exerts its effects on serotonin metabolism? Is it mediated by the same photoreceptor system as the alerting effects? • Does the serotonin metabolism effect explain the findings for increased daily light dose on mood and social behaviour in healthy adults? • Are the acute behavioural effects of higher daytime light exposure large enough to throw illuminance recommendations into question? Should illuminances be based on more than only visual requirements?
2.3 Skin-mediated effects	• Windows and skylights influence thermal sensations, but human adaptability makes the acceptability of conditions difficult to	• This is an information vacuum, where data are required to support practical choices about the built environment.	• The relative importance of one element or another is likely to be contextual, therefore specific investigations for different settings and

Section	General findings	Strength of information	Open Questions
	predict. • UVB radiation is important for vitamin D synthesis but also causes sunburn and skin cancer. UVA radiation is not useful for vitamin D production and causes sunburn and skin cancer. • Windows do not transmit UVB and transmit only small quantities of UVA. • During winter at high latitudes (far from the equator) there is very little UVB radiation and no possibility of vitamin D synthesis in the skin. • Many people who do not take vitamin D supplements and who avoid direct summer sun show signs of vitamin D insufficiency. This might place them at risk of disease.	• The action spectrum for vitamin D synthesis is well established, as are the spectra for sunburn and skin cancer. • There is debate concerning the necessary circulating level of vitamin D for good health and its role in physical health beyond regulating calcium uptake for bones and teeth. • There is debate concerning the need for a minimum daily UV dose to promote vitamin D metabolism. • There is no debate that this UV dose cannot be provided through windows.	populations will be needed. • The medical community needs to determine the healthy range of circulating vitamin D, and to identify safe ways to maintain this level through UV exposure and through oral supplements.

4 Conclusions

The conclusions of the full review may be broadly summarised as:

- Human well-being relies on regular exposure to light and dark each day.
- Daylight is the most energy-efficient means to deliver the light exposure, when it is available.
- Uncontrolled daylight also can cause problems: veiling luminances that reduce visibility, visual discomfort, thermal discomfort.
- The optimal pattern of light and dark exposure, as well as the limits at which daylight control is needed, probably varies for different populations defined by age and individual differences.
- The desire for daylight as the source of the light exposure also depends on how the openings affect the space appearance, on the function of the space, and on cultural norms about privacy, enclosure, and view.
- A view of outdoors is also a contributor to well-being, particularly if it is a nature or an attractive view. Separation from the sky and the outside world is to be avoided.

The following top-priority research domains concerning the health and well-being effects of windows, daylight, and view flow from this analysis:

- Establish the optimal daily pattern of light and dark exposures for good mental and physical health.
- Determine how our buildings can help us to live in the healthy pattern of light and dark, taking into account the way we use windows and shading to control privacy, glare, and temperature as well as light exposures and view.

Everyday experience tells us that windows are desirable features in buildings. Empirical research tells us that daylight through windows allows us to see, regulates important physiological functions in daily cycles, and promotes positive feelings and alertness. Views through windows and of spaces with windows make spaces look pleasant and provide the means to explore and overlook the environment, contributing to safety and restfulness. Further exploration of these research directions will provide the necessary details to integrate these effects with the building sciences, leading to practical guidance for the architectural community concerning the right balance between the considerations for daylight, view, ventilation, temperature control, and energy use.

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