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IRC-RR-325

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The Physiological and Psychological Effects of Windows, Daylight, and View at Home: Review and Research Agenda

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Jennifer A. Veitch and Anca D. Galasiu

Executive Summary

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 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” (Commission Internationale de l'Eclairage (CIE), 2004/2009):

1. The daily light dose received by people in Western [i.e., industrialized] countries might be too low.
2. Healthy light is inextricably linked to healthy darkness.
3. Light for biological action should be rich in the regions of the spectrum to which the nonvisual system is most sensitive.
4. The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.
5. The timing of light exposure influences the effects of the dose.

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, making it time for a renewed examination of the literature. Moreover, there has been scant attention paid to the role of daylight in residential buildings, which is the focus here.

This 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, whether their interests are general or specific to daylighting for residences. The conclusions may be broadly summarised as:

1. Human well-being relies on regular exposure to light and dark each day.

2. Daylight is the most energy-efficient means to deliver the light exposure, when it is available.

3. Uncontrolled daylight also can cause problems: veiling luminances that reduce visibility, visual discomfort, thermal discomfort.

4. 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.

5. 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.

6. 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.

7. Using daylight to deliver useful light is sustainable only in concert with the effects on the building envelope, ventilation, and overall energy balance. These require climate-based and locally specific solutions that respect other building system considerations and regulations.

The following three top-priority research domains flow from this analysis:

- Establish the optimal daily pattern of light and dark exposures for good mental and physical health.
- Determine how our homes 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.
- Develop design solutions and technologies for different climates that deliver healthy light, warmth, view and fresh air with the minimum of energy use.

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List of Abbreviations and Acronyms

ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers
CBT: core body temperature
CCBFC: Canadian Commission on Building and Fire Codes
CEC: California Energy Commission
CEN: European Committee for Standardization
CIE: Commission Internationale de l'Eclairage
DA: daylight autonomy
DGP: daylight glare probability
DLMO: dim light melatonin onset
fMRI: functional magnetic resonance imaging
IBPSA: International Building Performance Simulation Association
ICC: International Code Council
ipRGC: intrinsically photoreceptive retinal ganglion cell
LED: light-emitting diode
lx: lumens/m^2, lux
N-VE: non-visual effect
PMV: predicted mean vote (thermal comfort)
RHT: retino-hypothalamic tract
RVP: relative visual performance
SCN: suprachiasmatic nucleus
UDI: useful daylight index
UGR: unified glare rating
UV: ultra-violet radiation (UVA, 315 – 380 nm; UVB, 280 – 315 nm)
V_λ : photopic vision spectral sensitivity curve (adaptation luminance > 10 cd/m^2)
V'_λ : scotopic vision spectral sensitivity curve (adaptation luminance < .0003 cd/m^2)
VCP: visual comfort probability
WHO: World Health Organization

1. Introduction

Windows, providers of daylight and view, are in vogue, brought to the forefront of consideration by professionals in architecture, lighting, photobiology and psychology. Energy and environmental concerns and health and well-being goals each have brought renewed attention to the value of windows as a matter of debate and discussion in both the intellectual and practical lives of these fields. The professionals in these dialogues share a common goal of providing healthful built environments, but at present lack an integrated view that will lead to changed recommendations and guidance taking into account the most recent information.

Three substantive reviews of the state of the art were completed nearly ten years ago. Farley and Veitch (2001) and Boyce, Hunter, and Howlett (2003) focused on daylight and windows in workplaces. These reviews benefited from the fact that most studies of the effect of light, lighting, and daylighting on people take place in office settings and primarily include generally healthy adults in their early to middle working years. The reviews both concluded that windows and daylighting are desired by most employees and that they are contributors to health and well-being. Boyce et al. (2003) also concluded that although providing windows in a commercial building costs more than a solid wall, good daylighting can have financial benefits for organizations.

The International Commission on Illumination (know as CIE, the acronym of its French name, Commission Internationale de l'Eclairage) focused on developing general scientific principles for non-visual ocular light exposure, based on the evidence available through 2003 (CIE, 2004/2009). This review encompassed fundamental photobiology, therapeutic applications, and general lighting applications. The report established five principles of healthy lighting:

1. The daily light dose received by people in Western [i.e., industrialized] countries might be too low.
2. Healthy light is inextricably linked to healthy darkness.
3. Light for biological action should be rich in the regions of the spectrum to which the nonvisual system is most sensitive.
4. The important consideration in determining light dose is the light received at the eye, both directly from the light source and reflected off surrounding surfaces.
5. The timing of light exposure influences the effects of the dose.

In recognition of the intense interest in the topic and the pace of publications, the CIE report included a bibliographic list of papers published after the report's completion in 2003 but before its publication in 2004 (CIE, 2004/2009). The publication pace has not slackened since then, and it is time for a renewed examination of the literature on the effects of lighting and daylighting on health and well-being. This review, unlike previous reviews, has residential buildings as its particular focus. The residential setting is in many respects more challenging than commercial sectors because it encompasses all population groups and a broader range of activities.

This report will narrow the gap between fundamental science and building practice by achieving two objectives:

- to review the scientific literature concerning the physiological and psychological effects of windows and view, particularly in residences; and,
- to develop a research agenda aimed at supporting architectural and lighting design solutions that would contribute to residents' health and well-being.

The review starts from the World Health Organization (WHO) definition of health: "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1948). Thus, the goal is not only to eliminate bad design practices; rather, it is to support design and practice guidance that will create positive good for people in their homes.

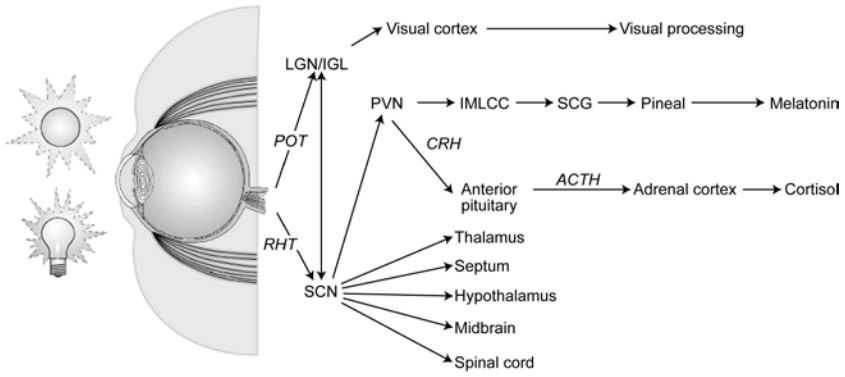

Figure 1. *Pathways from eye to brain (CIE, 2004/ 2009). Simplified schematic diagram of two eye-brain pathways. Light received by the eye is converted to neural signals that pass via the optic nerve to these visual and non-visual pathways. POT = Primary optic tract. RHT = Retino-hypothalamic tract. 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.*

The primary emphasis in this review is on the effects of windows and view in residential buildings: What physiological and psychological effects arise in people in response to ultraviolet and visible solar radiation received through openings in the building envelopes of their residences? These openings may be windows, skylights, or other light-redirection technologies. The internal processes by which this solar radiation influences health and well-being provide the structure for the review.

Most of the review is concerned with light received by the eye. Light is visible radiation in the range 380 – 780 nm (CIE, 2011b). It operates through two pathways from the eye to the brain, one visual and one non-visual (Figure 1). The visual pathway through the primary optic tract encompasses visual performance, perceptual judgements, and cognitions concerning the scene. The non-visual pathway, beginning with the retino-hypothalamic tract, encompasses at least circadian regulation and acute effects on alertness and mood, but could include other processes that have not yet been fully understood to be connected to light exposure.

Solar radiation received through skin exposure (including ultra-violet radiation [the range from 280 to 380 nm will be considered here] and infra-red radiation) also influences health and well-being. The thermal sensations resulting from infra-red radiation are not a primary focus of the present review except as they interact with visual processes.

This review is aimed at developing an understanding of the effects of daylight and windows to support general architectural principles that can be expected to apply broadly. In this context the review is not intended to address therapeutic situations in depth. Light therapy to treat various clinical disorders, particularly for seasonal affective disorder and for sleep disorders, is well-established. The consensus guidelines for light therapy require specific dosage (intensity and duration) and a specific time of day (Lam & Levitt, 1999; Michalak, Lam, & Levitt, 2002; Ravindran et al., 2009; Terman et al., 1995). These treatments require electric light for reliable delivery, and therefore this literature is not included in this review. Evidence that light or view from windows can contribute to either prevention or treatment of health problems is included where appropriate.

Windows can also contribute to well-being through their contributions to ventilation, but these effects lie outside the scope of this review. However, the final section of the review is a brief consideration of the broader building science issues that require balance against the daylight and view goals for windows in residential buildings. The report concludes with a research agenda that integrates all aspects of the literature review.

2. Effects on Well-being

2.1 Visual System

2.1.1 Visual performance.

2.1.1.1 Fundamentals of seeing. The best-understood of the processes triggered by the light admitted by windows and daylight is visual performance. Indeed, enabling people to see objects and tasks is the primary purpose of daylighting, and the support this provides to daily activities is an important contribution to well-being. Independent of the light source, the Relative Visual Performance (RVP) model predicts that performance of the visual component of a task is a function of the adaptation luminance and the size and contrast of the visual task (Rea & Ouellette, 1991). Figure 2 illustrates the model for four task sizes. It is evident that visual performance for most tasks is more strongly affected by the task size and contrast than by the quantity of light, at least for the young adults on whom the model is based. For this reason the model has been described as a “plateau and escarpment” model (Boyce, 2003). Except for very small and very low-contrast tasks (the escarpment), relative visual performance is high across a wide range of light levels (the plateau).

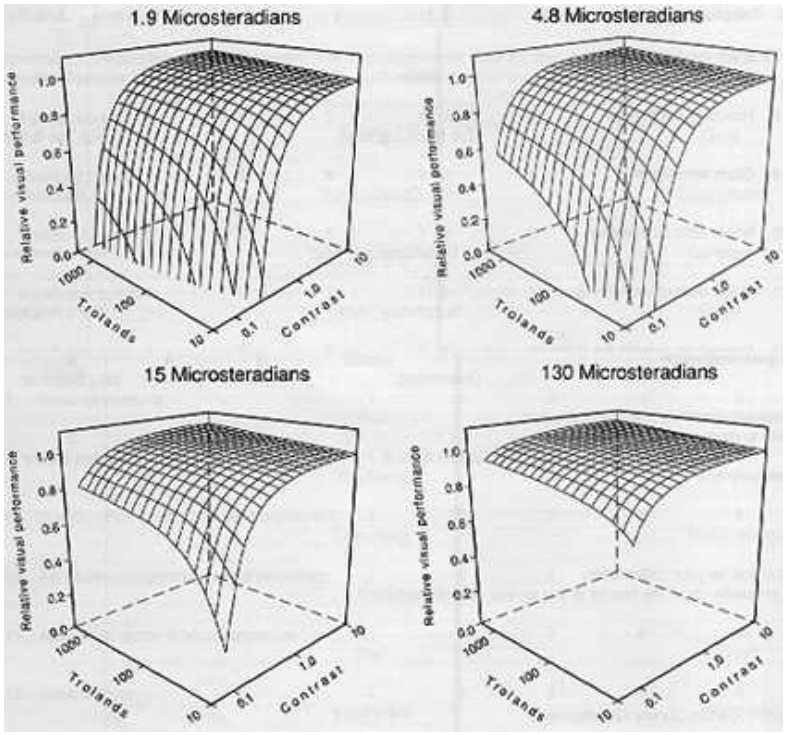

Figure 2. *Relative visual performance (RVP) model from (Rea & Ouellette, 1991). Each chart shows the effect of light level (retinal illuminance in trolands, x axis) and task contrast (z axis) on relative visual performance (y axis) for a task of a given size (shown in the title above the chart).*

Visual performance is partly a function of depth of field, which is greater when pupil size is smaller — as occurs when the retinal illuminance is higher. Short-wavelength light reduces pupil size (Berman, Fein, Jewett, Saika, & Ashford, 1992), which under tight experimental control increases depth of field and improves visual performance (Berman, Fein, Jewett, & Ashford, 1993, 1994). Interestingly, brightness perception is also greater for a given illuminance when the relative contribution of short-wavelength light is greater (Berman, Jewett, Fein, Saika, & Ashford, 1990). This effect might lead to the prediction that visual performance will be greater in daylight (which is generally richer in short-wavelength light) than under common interior electric light sources. Extensive attempts to show that visual performance under realistic viewing conditions responds to the spectral content of electric light have largely failed (Boyce, Akashi, Hunter, & Bullough, 2003; Halonen, 1993).

It remains true, however, that daylight is the most energy-efficient light source during daylight hours. Our understanding of visual performance shows that provided the daylighting system admits even a modest amount of daylight, the visual needs of many occupants to see fine details will be supported. Predicting the daylight available for visual functions is

accomplished using various modelling methods; climate-based daylight modelling permits calculation of the amount of time during the year that a specified light level will be achieved in a specific design at a specific geographic location (Mardaljevic, 2008).

Lighting recommendations and the usual values used for these predictions usually assume a young adult viewer. Older adults and those with visual impairments might need additional light to achieve acceptable visual performance. In such cases, their lighting needs for vision are well established in documents such as the *CIE Guide to Increasing Accessibility in Light and Lighting* (CIE, 2011a). This guide compiles information concerning, for example, the decline in contrast sensitivity, the reduction in useful visual field, and the decreased tolerance for glare, which all occur as people age and which are also problems for people with certain visual disorders. The decline in contrast sensitivity can be compensated for by increasing the luminance level of the task to be viewed, as one would predict from the general form of the models in Figure 1. (Another possibility would be to increase the size of the detail to be viewed.)

This increase in luminance must be handled with care, however, so that there is no scatter of light on the retina. Stray light, known as a veiling luminance, reduces the apparent contrast of the task and thereby reduces its visibility. This problem increases in severity with age (CIE, 2011a; Haegerstrom-Portnoy, Schneck, & Brabyn, 1999). Moreover, when the unwanted light is removed the time required to recover full vision is longer for an older person than a young one.

Field measurements of daytime residential light levels in both the USA and the Netherlands have found that the home-dwelling elderly rate their light levels as adequate even when they are considerably lower on average than recommendations based on visibility (Aarts & Westerlaken, 2005; Bakker, Iofel, & Lachs, 2004; Charness & Dijkstra, 1999). This is poignant when one considers that two field investigations have demonstrated improved quality of life in response to increased light levels in the homes of the elderly or partially sighted (Brunnström, Sörensen, Alsterstad, & Sjöstrand, 2004; Sorensen & Brunnstrom, 1995).

It is not clear why people have made the choice of low light levels, although several suggestions have been made. Bakker et al. (2004) noted that for most people daylight was the principal light source, and yet many participants had their window shades drawn regardless of the time of day. They did not collect systematic information about the reason for this, but anecdotally reported that avoidance of uncomfortable visual contrast, avoidance of discomfort, privacy and thermal comfort were all cited as reasons for having shades drawn. They asked respondents whether cost was a factor in not using more light, and found that in general it was not a factor. Bakker et al. concluded that promoting the use of translucent, rather than opaque, window treatments would provide for higher light levels and more use of daylight while also addressing these other concerns.

2.1.1.2 Assessment: Visual performance and daylight. Our knowledge concerning visual performance is very robust for achromatic (black-and-white) tasks. None of the models address chromatic tasks. Fundamental vision science findings apply in any setting, so that knowledge derived from laboratory research applies equally in residences as in schools or workplaces, provided the application is to the same population, defined in terms of age and visual health. Research into age-related changes in vision and the specifics of the changes in contrast sensitivity both with age and various visual diseases continues, and might be expected to result in changed recommendations for residential lighting, particularly related to controlling glare in order to maintain visibility for specific populations. Considering the issues as applied to residential settings, the most interesting research questions concern the consistent findings of low illuminances in residences, particularly in those occupied by people whose visual needs would lead one to think that higher levels would be beneficial. Assuming that the residences made their own light level choices, what are the reasons for these choices, and how might residents be encouraged to make more and better use of daylight to provide for their visual needs?

2.1.2 Spatial appearance.

2.1.2.1 Appearance research. The light admitted from the window or skylight illuminates the space, which clearly influences its appearance. Architects develop intuitive or phenomenological appreciation of the interplay of daylight, sunlight, and space (Bruder, 2011; Hawkes, 2011), but their descriptive and analytical approaches are foreign to more scientifically-oriented disciplines and (perhaps intentionally) seem to have little direct influence on researchers or formal recommendations, codes, and standards. The researchers, in turn, attend primarily to the mechanics of the presence of windows, their sizes and the type of glazing as influences on the appearance of the space.

Rooms with windows are generally perceived more favourably that those without, but other contextual factors influence these judgements. For example, Tognoli (1973) found that a university room with windows appeared more pleasant than one without, but that judgements of its comfortableness were simultaneously influenced by the room decorations and the qualities of the chair in which the participant sat. Such results make it difficult to make broad generalizations from research to design, and lead to the caution that generalization from one setting (e.g., offices or schools) to another (e.g., residences) is tenuous where perceptual judgements are concerned. The general finding is that windows are preferred in most settings (Collins, 1976; Farley & Veitch, 2001), but specific guidance concerning design features should rest on studies of the setting in question.

Kaye and Murray (1982) examined appearance ratings of watercolour perspective drawings of a residential living room, displayed as colour slides. When the image showed the living room as having a window, the room was perceived more favourably on scales involving socio-aesthetic judgements (more inviting, friendly, beautiful, bright), mood (less closed, drab, dead) and size (larger, more spacious).

Clearly a window is a desirable feature in a living room; however they are not uniformly desired in all room types. American undergraduate students reported preferring either no window, or a small one (clear or translucent) for a home bathroom, but one large or two medium-sized clear windows in a family room or living room (Butler & Biner, 1989). Their skylight preferences also varied for different spaces, being lower for bathrooms and higher for living rooms, dining rooms, and kitchens among the residential spaces rated (Butler & Biner, 1990). An important limitation of these two studies is that they were surveys conducted in classroom settings in which the respondents (university students) reported preferences on relative scales in the absence of any physical anchors.

Notwithstanding this limitation, the results make intuitive sense and are consistent from one to the other. Butler and Biner (1990) found that the best predictor of skylight preferences was the influence of the skylight on the judged spaciousness of the room. This suggests that spaciousness is not a quality wanted in all room types. Other characteristics are more important in other room types. For example, their window preference study found privacy to be the best predictor of residential bathroom window preference (Butler & Biner, 1989).

Environmental aesthetics researchers seek understanding of the influence of architectural features on space appearance and environmental preference. Two theories dominate: Kaplan and Kaplan (1989) suggested that humans prefer environments that are rich in mystery and complexity, but coherent and legible. That is, according to this theory people prefer orderly scenes where elements are in expected places, but which offer the possibility to reveal more if one enters farther in. Testing of predictions based on this theory has provided mixed results (Stamps, 2004). Stamps (2007) has proposed an alternate theory that he has called “permeability theory” in which spaciousness and safety are important predictors of preference. Permeability refers to the boundary around the individual — walls and ceiling in the case of interiors. A permeable boundary has openings through which one can either see or

move. Spaciousness is important to safety because it implies distance between oneself and any danger; it provides a vista from which one can survey the world.

Both theories might account for window preferences to a degree, but permeability theory could also account for the differences in preferences for different room functions that Butler and Biner (1989, 1990) observed. In a space where one might be more vulnerable to danger, such as a bedroom or a bathroom, privacy and smaller windows offering less view in are wanted or preferred. In more public areas such as living rooms or kitchens, windows and skylights have higher preferences. These preferences might have cultural or social origins: Lau, Gou, and Li (2010) found that in the high-density environment of Hong Kong, daylighting desires were less important to residents' preferred window configurations than were the needs to preserve privacy for eating, sleeping, and using the bathroom.

Windows and skylights create rougher, more permeable boundaries than do unbroken walls; one can see farther through windows and skylights than through opaque walls. Increased boundary roughness in simulated rooms contributes to increases in judged spaciousness (Stamps & Krishnan, 2006). Stamps (2010) examined the relations between perceptions of enclosure and spaciousness and the physical conditions of boundary permeability, light levels, and horizontal area in a variety of interior and exterior settings and found consistent results supporting hypotheses that more open boundaries, higher light levels, and larger horizontal areas reduce the feeling of enclosure and increase the feeling of spaciousness. Thus, for settings where less enclosure and more spaciousness are the desirable characteristics, windows and skylights will contribute favourably.

The desired degree of permeability, or the desired size of window, is not precisely understood for residential environments. Most of the literature on preferred window size is based on office environments (Butler & Steuerwald, 1991; Inui & Miyata, 1973; Keighley, 1973a, 1973b; Markus, 1967; Ne'eman & Hopkinson, 1970). Inui and Miyata (1973) developed a predictive model, finding that Japanese participants judged the spaciousness of a scale model of an office based on the average horizontal illuminance on the work plane, the room volume, and the visual angle of the window at the viewing position (expressed as a percentage of the view); the coefficients varied with the sky luminance (of a diffuse artificial sky). These equations showed good agreement to judgements of a real office. A subsequent experiment in a scale model described as a living room observed similar functions, with the most important contributors to judged spaciousness being illuminance and window size (Inui & Miyata, 1977); spaciousness correlated highly with satisfaction.

If we accept that results generalize from offices to residential living rooms, the best available specific direction comes from Keighley (1973b), who observed that the preferred window dimensions lay between 1.8 and 2.4 m in height and slightly wider than tall. Butler and Steuerwald. (1991) observed that preferred window shape varies with office size, being less horizontal in a smaller office; preferred window size was larger when the view was more desirable. These results are consistent with those of Ne'eman and Hopkinson (1970), who also varied room shape. It is likely that preferred window dimensions for residences also vary in relation to the view of outdoors, with larger windows being preferred when the view is more attractive or less obstructed. The value of the view is discussed below (section 2.1.4).

Interestingly, research on the effects of glazing type on interior room perceptions, to date, shows consistent results across office and living room settings. One study was conducted in Denmark and involved ratings of a scale model of a simple cellular office with various glazings viewed under a real sky (Dubois, Cantin, & Johnsen, 2007); one study was conducted in Canada using a scale model of a living room with various glazings viewed under a real sky (Pineault & Dubois, 2008). Dubois (2009) compared the results of these two experiments to a third, in which participants viewed the living room model under an artificial sky. The results are in good general agreement in that glazings with higher transmittance were correlated with judgements that the rooms were brighter, more natural, more pleasant, and more beautiful

(spaciousness was not one of the scales used). However, they also led to perceptions of higher glare discomfort, discussed in the following section.

These experiments achieved changes in transmittance using coated glazings, and the coatings varied in both transmittance and colour shifts. Pineault and Dubois (2008) observed that under various natural sky conditions the glazings with a stronger unidimensional green shift were the least preferred, whereas glazings that shifted the spectrum (interior relative to the exterior daylight) in both the green-red (a*) and blue-yellow (b*) dimensions led to better ratings of the interior appearance. However, this study did not include any glazings with unidimensional red (warmer) shifts, which others have suggested are preferred over cooler, more greenish shifts (Cuttle, 1979).

2.1.2.2 Assessment: Spatial appearance in dwellings. Strong evidence shows that for many (but not all) room types and settings, people prefer to have windows or skylights. The presence of windows makes a room appear more spacious and reduces the feeling of enclosure, likely because they change the perceived permeability of the spatial boundaries. In residential settings, this decreased enclosure is desired in some rooms (living rooms and kitchens), but not in others (bathrooms). There is some evidence for cultural influences on the preferred degree of enclosure or permeability through windows and skylights, but further investigation is warranted. Specific architectural guidance on window or skylight size or placement in residences does not exist; the only data available are old and based on offices in the UK. Limited evidence suggests that window treatments affecting colours should avoid creating greenish shifts. There also is no information available concerning the psychological effects of dynamic changes in daylight, or the changing patterns of sunlight, on spatial appearance in the way that architects understand intuitively.

Some might consider residential aesthetics to be desirable upgrades but not essential to the provision of shelter — that is, nice, but not necessary. Conversely, inhabiting a home that is judged to be more attractive or more spacious may be considered a psychological good in itself. In this context consider the evidence that higher residential quality (as judged by objective scales of the physical environment) benefits both physical and psychological health (Evans, Wells, Chan, & Saltzman, 2000; Gifford & Lacombe, 2006). Using windows and daylight to provide better quality in the form of improved spatial appearance would be expected to contribute to these benefits.

2.1.3 Discomfort.

2.1.3.1 Predictive models. High light levels on a task can increase visibility, but stray light scattered in the eye decreases visibility; intense light directed at the eye can cause visual discomfort. This well-known phenomenon has been extensively studied for many decades, resulting in the establishment of systems to predict discomfort from electric lighting in workplaces such as the Visual Comfort Probability (VCP) (Committee on Recommendations for Quality and Quantity of Illumination, 1966) and the Unified Glare Rating (UGR) (CIE,1995). Although these metrics differ in their details, each predicts discomfort based on the luminance of the source, its position and visual size relative to a specific viewing position, and the viewer's adaptation luminance. Limitations of these systems for electric lighting are well known; for example, they work for large uniform sources but not for nonuniform sources nor for arrays of small sources (Eble-Hankins & Waters, 2009). Moreover, they are not applicable directly to glare from windows or daylight (Boubekri & Boyer, 1992), leading to the development of separate indices for this problem, such as the Daylight Glare Index (Hopkinson, 1972), its modifications by Nazzal (2001) and by Fisekis, Davies, Kolokotroni and Langford (2003), and more recently the Daylight Glare Probability (DGP) (Wienold & Christoffersen, 2006).

Of the daylight glare prediction models, the DGP seems the most robust at present (van den Wymelenberg, Inanici, & Johnson, 2010), but all of the models have weaknesses and

inconsistencies (Osterhaus & Veitch, 2011, in press). For the present purpose, the greatest problem is that all of the models have been developed for office, or at best for workplace, applications. There are no predictive models for window or daylight glare in homes, but there is evidence from office lighting research that discomfort is partly determined by non-lighting variables, such as task involvement (Osterhaus & Bailey, 1992) and the interestingness of the scene outside (Tuaycharoen, 2011; Tuaycharoen & Tregenza, 2005) and its content (Yun, Shin, & Kim, 2011). A recent conference workshop concluded that much remains to be learned about visual discomfort from unwanted light, including consideration of the difference between comfort (or its opposite, discomfort) and acceptability (i.e., sometimes what is uncomfortable is nonetheless acceptable, for example if it offers another feature that is highly valued), and an understanding of the fundamentals underlying the discomfort experience across various real settings (Osterhaus & Veitch, 2011, in press).

The literature on the effects of glazing type on interior perceptions identified an important paradox (Dubois, 2009; Pineault & Dubois, 2008), in which the same conditions that led to higher ratings of beauty and pleasantness (those with high visible transmittance) also led to higher ratings of discomfort. This could lead to a design conflict unless one considers the possibility for home occupants to control their shading devices to reduce the light ingress when it is unwanted and to have light and view at other times. The strategy will be successful only if the resident takes advantage of the view at those other times. The evidence suggests that this might not happen: The elderly experience slower recovery from discomfort (CIE, 2011a) and might therefore be more likely to take strong measures to avoid its occurrence. Bakker et al. (2004) observed that the housebound elderly residents in their survey of light levels often had all of the curtains drawn on the windows, some to reduce discomfort and some for other reasons, including thermal comfort and privacy.

There have been a few contemporary field studies of shading device use in offices, but we were unable to find systematic studies of home shading devices use in the published literature. Even the office data is not consistent in its conclusions: Inoue, Kawase, Ibamoto, and Takakusa and Matsuo (1988) monitored the windows of four high-rise office buildings in Tokyo and found that 60% of the blinds were not operated at all throughout the day. For the other 40%, the blinds position varied with façade orientation, time of day, and sky condition; generally this seemed to follow a pattern related to whether or not direct solar radiation above a threshold reached the occupants of the room; the threshold range they cited was wide, between 11-58 W/m^2. Reinhart and Voss (2003) monitored one façade of one office building in Freiburg, Germany for several months and concluded that blinds were manually closed to avoid direct sunlight over 50 W/m^2. However, Mahdavi and Proglhof (2008) monitored various facades in several buildings in Austria, and concluded that it was not possible to correlate shading device use to incident irradiance. Investigators from Canada, the USA, and the UK have also reported office occupants chose shading configurations that were not dependent on the sun position or the daily or seasonal climatic conditions (Foster & Oreszczyn, 2001; Rea, 1984; Rubin, Collins, & Tibbott, 1978). Given that window shading choices may differ significantly in the residential setting and may have different triggers for their configuration or adjustment, this topic is ripe for examination.

2.1.3.2 Assessment: Discomfort from residential windows. Even for workplaces, our ability to predict discomfort associated with light from windows is limited; for residential settings it is nonexistent. Office research suggests that non-lighting variables, such as task involvement and the quality of the view, influence the experience of discomfort caused by unwanted light – glare – from windows. This literature has not yet been applied to study residential settings, and no studies in any setting have examined age-related changes in visual discomfort from daylight, sunlight, or windows. This is a particularly important gap in residential research because both the very young and the very old spend relatively more time in their homes and are most likely to be

affected by the conditions there, whereas most design recommendations are based on workplace research where spaces are occupied by middle-aged, healthy adults.

2.1.4 Stress and restoration.

2.1.4.1 Effects of outdoor views. The preceding sections all concern light admitted through windows and skylights. Clear windows and skylights also provide a view of outdoors, including information about the exterior climate and time of day. This information provision is an acknowledged function of a window (Butler & Biner, 1989; Markus, 1967). There is longstanding and persistent interest among psychologists in the effects of exterior environments on people of all ages and in many settings, from homes to hospitals to workplaces.

The starting point for this work is the psychological concept of *stress*, which has many definitions that share a commonality in describing "…a process in which environmental demands tax or exceed the adaptive capacity of an organism, resulting in psychological and biological changes that may place persons at risk for disease" (Cohen, Kessler, & Gordon, 1997) (p. 3). These environmental demands may be objective physical demands or subjectively perceived demands and the outcomes studied may be affective (emotional), behavioural, or physiological, depending on the discipline of the researcher. The research considered in this section focuses neither on the demands (stressors), nor the outcomes (strain or disease), but on the possibility of using the physical environment as viewed or experienced to reduce the intensity of the demands or the severity of the outcomes.

The seminal paper in this tradition is Ulrich's (1984) paper in the journal *Science,* reporting his finding that hospital patients with a view of green spaces, as opposed to those with a view of a blank brick wall, recovered more quickly from surgery and required less post-operative pain medication. At the time, the possibility that higher light exposure might be beneficial to health was not known, and the interpretation of this finding was that the greater opportunity to see nature was the cause of this finding. The possible role of light exposure is discussed below; in this section the relevant fact is that indeed, the content of the view matters.

Several investigations have shown that the restorative benefits of a view of nature accrue in laboratory settings when the view is of a photograph or a slide and in real settings when the view is through a window. (Other literature not reviewed here has observed similar effects with immersive exposures in real outdoor environments, with and without exercise.) The benefits are physiological, behavioural, and affective. For example, university students viewing images of natural scenes showed faster physiological recovery from a prior stressful experience than those who viewed built environment scenes (Hartig, Mang, & Evans, 1991; Ulrich, Simons, Losito, & Fiorito, 1991). Berto (2005) induced mental fatigue (a stress outcome) with a demanding task, then exposed participants to photographs of nature scenes, built environment scenes, or geometric patterns. Those who saw the nature scenes did better on the second round of the demanding task than the others.

Rachel Kaplan, in contrast, surveyed apartment residents in their homes (in Ann Arbor, Michigan) to relate the views from the homes to residents' satisfaction and well-being, finding that having nature elements in the view was important to both, but more predictive of the satisfaction measures (Kaplan, 2001). These benefits are not limited to middle-aged adults (Kaplan's study population); this is perhaps the only topic in this review for which extensive literature exists for various age groups and geographical populations. Talbot and Kaplan (1991) had previously found that elderly apartment residents whose homes overlooked nature settings were more satisfied with their homes (an affective outcome). Tang and Brown (2006) assessed cardiovascular outcomes among elderly women in a nursing home as they viewed rooms with no window, a view of the built environment, or a natural landscape. Both outdoor views lowered blood pressure and heart rate (in comparison to the windowless room), but the nature view had a larger effect. An American study of children living in a large housing project found that girls who lived in an apartment with a nature view showed better concentration, ability to delay

gratification, and impulse inhibition than those whose home views did not include nature (Taylor, Kuo, & Sullivan, 2002), although nearby nature had no effect on these scores for boys.

The precise mechanism for these benefits is not known (Hartig, 2008). One possibility, known as Attention Restoration Theory, is that natural environments have characteristics that promote exploration rather than directed attention, thereby allowing directed attention abilities time to replenish (Berman, Jonides, & Kaplan, 2008). This explanation can account for the cognitive benefits of nature exposure, but less clearly explains the psychophysiological or affective results. Another possible explanation is Wilson's (1984) biophilia hypothesis, which holds that humans are intrinsically drawn to natural environments, particularly those that were important evolutionary settings. Heerwagen (2011) has proposed that this might explain the general preference that most people have for daylight.

Images of nature compared to images of built environments could be said to differ both in the degree of natural content and in attractiveness, depending on the selection of the images. Perhaps the effects relate to image (or view) attractiveness, and not to its content. One study of office workers separated the quality of the view from its content, and examined the effects of both on measures of office impressions (appraisals of the appearance of the space), physical and psychological discomfort and night-time sleep quality using path analysis to examine an underlying structural model (Ariës, Veitch, & Newsham, 2010). Views that had been independently judged to be more attractive were associated with reduced discomfort and, through the discomfort effect, with better sleep quality. Nature views had contradictory results with both direct and indirect effects on discomfort. There was a direct effect in which nature views increased discomfort, but a simultaneous indirect path through which nature views improved office impressions and contributed to the reduced discomfort associated with better office impressions.

Clearly, not every residential building can have a view of nature, and probably not every building can have an attractive view (natural or not); however, to the extent that these are available, site-specific choices of window placement and sizing can reveal views that will contribute to the inhabitants' well-being.

Evans and McCoy (1998) provided another perspective on the issue, observing that being understimulated can be stressful too, leading to boredom or, at worst, sensory deprivation. Thus, environments that lack a view outdoors, whatever its content, could be stressful for this reason. A view of outdoors, even if not predominantly a natural view, offers variety in the changing light, both predictable daily and seasonal patterns of colour and direction and less predictable changes from the weather. In this context, windows and skylights act as stress prevention tools as well as providing opportunities for restoration.

2.1.4.2 Assessment: Stress and restoration. Clear evidence from laboratory studies and a variety of field investigations shows the benefits of exposure to a view of outdoors, particularly nature views – although the latter finding might be modified to consider the attractiveness of the view, whether natural or built. The results are robust across settings from hospitals and workplaces to residences. Further investigation will be needed to elucidate the mechanism or mechanisms for these effects, which are physiological, cognitive, and emotional. The influence of aesthetic quality, as distinct from natural content, also remains an open question. Apart from its theoretical interest, this issue has important practical consequences for urban dwellings, where a nature view will not always be feasible.

2.1.5 Summary: Visual effects and windows. Both the light and the view through windows and skylights offer benefits to residents through visual processes. The best-understood process is vision itself; we know well how much light is needed to see common tasks. What we do not understand is why some people who need more light do not provide it for themselves. The limited evidence that does exist suggests that the answer lies in the balance between different needs, particularly the avoidance of discomfort. Discomfort accompanying light in residential windows is very poorly understood; there is almost no published research on this topic, and what there is tells us that we ought not to generalize from the office glare models to predict discomfort in homes. Furthermore, although it is possible to predict visual performance requirements for different age groups it is not possible to predict their experience of discomfort. It might be tempting to increase daylight penetration in the homes of the elderly in order to improve task visibility, but to do so would risk causing discomfort.

The presence of windows and skylights offers benefits through two dimensions of view: First, the effect of the window on spatial appearance, and particularly on the perceived spaciousness of the room. Here too, we have limited understanding of how this perception applies in residences and a better understanding of its application in offices. More information on the relative importance of various perceptions in different room types is needed, as is more information about the contributions of windows to these perceptions. In addition to size and shape, other window parameters also deserve attention, such as glazing type, shading features, and the use of shading devices. The conditions that lead to the greatest perceptions of spaciousness also give rise to the greatest risk of discomfort and potentially the least privacy, meaning that we need to understand better the trade-offs between these experiences at home. The limited evidence available today suggests that this trade-off might be culturally influenced; cross-cultural research is needed before recommendations based on one society are (perhaps mis-) applied elsewhere.

Second, a view of outdoors, particularly if it is a nature view, offers benefits that are manifested as feelings, as behaviours, and in physical health. Further research on the distinction between the attractiveness of the view and its content could prove helpful to ensuring that even where nature views are scarce (in urban settings, for example), good view quality is achievable through appropriate window sizing and location. Residential window design with an eye to preserving view (e.g., through positioning of mullions and other architectural elements), while also providing light for vision and spatial perception but controlling glare, also merits research attention.

2.2 Non-visual Ocular Systems

The preceding section concerned processes that begin with visual signals: None of those processes could occur in the absence of visual processing and interpretation of images detected because of light entering the eye and causing signals to be sent via the primary optic tract (see Figure 1). In this section we turn to processes triggered by light entering the eye that cause signals to be sent down the retinohypothalamic tract (RHT). Discoveries involving these non-visual ocular light signals have arguably breathed new life into lighting research, lighting technologies, and lighting applications.

Among the most immediate applications for this new knowledge has been lighting protocols to address maladaptation to shift work and to treat sleep disorders and some mood disorders. These studies are included here only to illuminate fundamental processes, unless there is a direct connection to residential daylighting systems.

2.2.1 Circadian regulation. Circadian regulation, by definition, involves a 24-hour cycle and thus, one must understand the effects of night-time exposure as well as its daytime counterpart in order to understand how residential window

light might influence these processes. This section begins with consideration of fundamental science.

2.2.1.1 Fundamentals: Melatonin. Melatonin is a hormone secreted by many cells throughout the body, but the dominant source of circulating melatonin is its secretion at night, in darkness, by the pineal gland (Arendt, 1998). All species that have yet been studied show this pattern of melatonin secretion in darkness (Arendt & Skene, 2005); thus its primary function is to initiate processes that occur nocturnally. These processes differ, of course, for diurnal (day-active) and nocturnal (night-active) species. Because the duration of its secretion will vary with the length of the night, it also signals seasonal changes that are important in some species (Arendt, 1998; Wehr, 1997). In humans its best-known function is to initiate sleep and to lower core body temperature (CBT). Light is the most powerful regulator of this hormone, although social cues and eating habits also influence it. Circadian regulation by light, indexed by changes in melatonin secretion, is a function of the timing, intensity, duration, pattern and spectrum of light exposure (Cajochen, 2007; Duffy & Czeisler, 2009).

The underlying rhythm of melatonin secretion is governed by the circadian clock in the suprachiasmatic nucleus (SCN), which is a structure in the hypothalamus. Its intrinsic rhythm runs at approximately 24 h 20 min in most people (Czeisler et al., 1999), but is coordinated to external conditions by the signals received through the RHT (Duffy & Czeisler, 2009). Acute light exposure at night can suppress the normal melatonin secretion; at first this was thought to require relatively high illuminances, over 2500 lx at the eye (Lewy, Wehr, & Goodwin, 1980), but now is known to occur at considerably lower illuminances, as low as 10 lx (Boivin, Duffy, Kronauer, & Czeisler, 1996; Brainard et al., 1988; Brainard, Rollag, & Hanifin, 1997). Differences in light exposure history and experimental methodology underlie the changing consensus, and it is now thought that very low light exposure, as low as candlelight, could acutely suppress melatonin secretion under some conditions (Duffy & Czeisler, 2009).

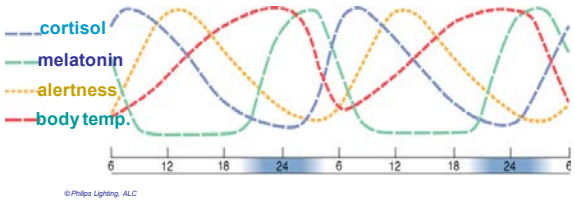

Figure 3. *Schematic diagram of four bodily functions that show circadian rhythms, in proper relation to one another. © Philips Lighting. Used by permission.*

Among the important conditions are the timing and pattern of exposure. Timing in this context means timing in relation to circadian phase. For a healthy day-active person, melatonin secretion peaks in the middle of the night ("biological night") and CBT reaches its nadir shortly after, as shown in Figure 3. During this time, the SCN is most sensitive to light exposure (Gillette & Tischkau, 1999). Light exposure early in the biological night, during the period when melatonin secretion is on the rise, tends to delay the CBT nadir. Light exposure later in the biological night (shortly after the CBT nadir) tends to advance the cycle, so that on the following day melatonin secretion and other processes will begin earlier. The SCN also is more sensitive following a long period in darkness (Duffy & Czeisler, 2009), and the darker this period, the larger the amplifying effect on a subsequent light exposure (Chang, Scheer, & Czeisler, 2011). Conversely, a period of exposure to bright light reduces subsequent effects of light on melatonin suppression (Hébert, Martin, Lee, & Eastman, 2002). These dynamic changes in light sensitivity of the circadian system do not, however, mean that there is a time of day when there is no response to light exposure (Jewett et al., 1997). The changing sensitivity means that at some times of the biological day, and as a result of the recent light exposure pattern, more or less light intensity of relatively shorter or longer duration is required to obtain a given physiological response.

The starting point for this response is the detection of light at the retina of the eye. Photobiology revolutionized ocular physiology in 2002 with the discovery of the intrinsically

photoreceptive retinal ganglion cell (ipRGC) in 2002 (Berson, Dunn, & Takao, 2002; Hattar, Liao, Takao, Berson, & Yau, 2002). The finding confirmed what had been suspected for some time, that the light signals to regulate circadian rhythms are functionally separate from the retinal level to the pineal gland (Brainard & Bernecker, 1995).

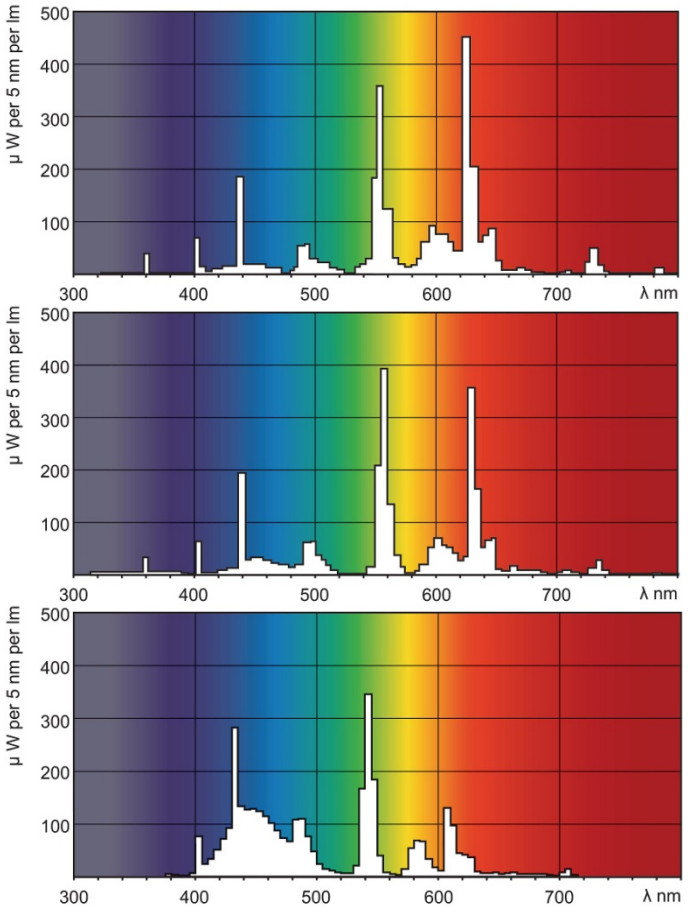

Figure 4. *Spectral power distributions for three T5 fluorescent lamps differing in correlated colour temperature. The top panel shows a 3000 K lamp, middle shows 4000 K, and bottom shows 17,000 K. All lamps have CRI > 80. © Philips Lighting. Used by permission.*

Part of the evidence in support of this separate pathway was the development of action spectra for melatonin suppression by light at night and the finding that this process is most sensitive to short-wavelength visual radiation with a spectral response curve different from that of the classical photoreceptors, rods and codes (Brainard, Hanifin, Rollag, et al., 2001). Several action spectra have been published, based on various mammalian species (rats, mice, humans) and various responses, including pupillary light responses (Lucas, Douglas, & Foster, 2001) and melatonin suppression (Brainard, Hanifin, Greeson, et al., 2001; Thapan, Arendt, & Skene, 2001). To date there is no firm consensus concerning the exact spectrum, with some authors interpreting the data to conclude that the peak spectral response of the system occurs at ~ 460 nm (Cajochen, 2007) and others at ~480 nm (Foster, 2005, 2011), whereas others have placed the peak somewhere in the range between 459 and 483 nm, without specifying exactly where (Brainard & Provencio, 2006).

The action spectrum question is not merely academic, but has important practical consequences. Manufacturers have developed new light sources that have relatively higher short-wavelength contributions than conventional sources (e.g., fluorescent lamps with correlated colour temperatures as high as 17,000 K) on the assumption that increasing daily exposure to short-wavelength optical radiation will prove beneficial to daytime alertness and night-time sleep quality among indoor workers. Figure 4 shows three examples of fluorescent lamp spectral power distributions, to illustrate the differences. The top and middle panels show 3000 K and 4000 K lamps, spectra found commonly in homes, institutions, and offices. The bottom panel shows the spectral power distribution for a 17,000 K lamp, designed specifically to increase the short-wavelength component. There is some evidence that the assumption concerning this increased exposure holds true: A 17,000 K lamp in an office environment did improve daytime alertness and night-time sleep quality in two studies (Mills, Tomkins, & Schlangen, 2007; Viola, James, Schlangen, & Dijk, 2008). Other authors have argued that the circadian effects of short-wavelength-enriched interior lighting on sleep phase need careful

consideration because the short term studies might not detect longer-term unwanted consequences. Interior electric lighting tends to be invariant over the seasons, so that increasing short-wavelength exposure with electric light could suppress normal seasonal variations based on charges in solar radiation (Vetter, Juda, Lang, Wojtysiak, & Roenneberg, 2011). The same question could apply to choices concerning tinted glazings for windows and skylights, although the scientific literature does not hold any studies that have examined this question.

Several authors have argued that the existence of a separate system for irradiance information via the RHT should lead to the development of a new metric for expressing the quantity of light (Brainard & Hanifin, 2005; CIE, 2004/2009). Classical photometry is based on the visual system and its spectral sensitivity as expressed in the V_λ (photopic) and V'_λ (scotopic) curves. It is evident that the ipRGCs do not follow either of these (see Figure 5); indeed, this finding was part of the identification of the ipRGC system (Brainard, Hanifin, Rollag, et al., 2001). Without such a metric it is difficult to compare experimental results from one study to another when the authors report only the light exposure in lux and provide few or no details concerning the spectral properties of the light source. Illuminance is a measure of the strength of the light signal to the photopic visual system, and without the spectral information about the light source one cannot calculate the strength of that signal to any other system including the circadian regulatory system. A new metric cannot meaningfully be established without an international consensus on the underlying action spectrum.

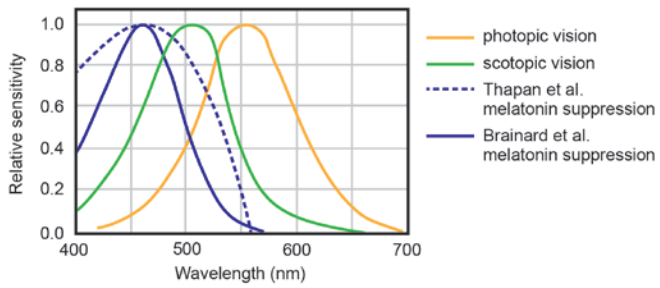

Figure 5. *The relative spectral sensitivity of ipRGCs is different from either of the spectral sensitivity functions for vision. The photopic vision curve (V_λ), applying when adaptation is above 10 cd/m^2, is shown in yellow, and peaks at 555 nm. The scotopic vision curve (V'_λ), applying when adaptation is below 0.0003 cd/m^2, is shown in green, and peaks at 505 nm. Two sets of experimental results based on melatonin suppression in humans are shown in blue (one solid line, Brainard, Hanifin, et al. (2001), and one dotted line, Thapan et al.(2001)), both peaking around 460 nm.*

Establishing a new metric in this way assumes that the physiological responses of this system are additive across wavelengths. Some evidence suggests this is not the case, as two studies of melatonin suppression following night-time exposure to commercial light sources did not observe the results that were predicted based on an action spectrum similar to those shown in Figure 3. It appeared from the results that the longer-wavelength radiation acted in opponency to the shorter-wavelength radiation, reducing the melatonin suppression effect (Figueiro, Bullough, Bierman, & Rea, 2005; Figueiro, Rea, & Bullough, 2006). Spectral opponency is one possible explanation for this finding, but this discussion is complicated by the mounting evidence that there is interplay between the rods and cones of visual responses and the ipRGCs (Jasser, Hanifin, Rollag, & Brainard, 2006; Revell & Skene, 2007). It appears that ipRGCs, which are irradiance detectors, do influence visual processing. They are the principal controllers of the pupillary light response, but also have projections to the brain's visual processing centres (Brown et al., 2010). Conversely, cones appear to contribute to circadian entrainment, at least in the initial stages of light exposure (Gooley et al., 2010).

2.2.1.2 Fundamentals: Health outcomes. The familiar daily activity cycle of sleeping and waking is the most obvious circadian rhythm, but many physiological systems show daily rhythms, including the cardiovascular and metabolic systems (Rüger & Scheer, 2009), immune system (Lange, Dimitrov, & Born, 2010;

Roberts, 2000), and skin (Verschoore, Poncet, Krebs, & Ortonne, 1993). Each of these systems depends on the rhythm of light and dark to maintain the necessary pattern of physiological processes to maintain physical and mental health. Circadian rhythms are also seen in diseases including rheumatoid arthritis (Cutolo, 2011), myocardial infarction (Rodriguez et al., 2003; Rüger & Scheer, 2009) and seborrheic dermatitis (Verschoore & Ortonne, 1993).

Disruption of the usual pattern of light and dark exposure, for example by missing sleep for a night, results not only in a changed pattern of melatonin secretion (as discussed above), but also can reduce immune response (Irwin, 2002; Irwin et al., 1996), placing the individual at risk for infectious disease (Bryant, Trinder, & Curtis, 2004). Beauchemin and Hays (1998) found that patients on the sunnier side of a cardiac intensive care ward showed lower mortality rates than those on the less-sunny side, even after controlling for obvious confounds such as disease severity. They lacked data to explain the reason for this effect, but the stronger circadian signal and associated improvement in circadian regulation is one possible explanation. (In that setting, view is an unlikely explanation, given the illness severity and the fact that patients are mostly flat on their backs.)

The observation that night-shift workers are at increased risk for ill health and particularly for breast cancer (Hansen, 2001; Schernhammer et al., 2001) has motivated extensive investigation into the effects of night-time light exposure on melatonin secretion and circadian rhythms. The question is not yet answered definitively (Costa, Haus, & Stevens, 2010; Kolstad, 2008), and new hypotheses as to specific mechanisms are under discussion (Erren, Groß, & Meyer-Rochow, 2011). Overall, the 2004 conclusion of the CIE, that healthy lighting encompasses the equal need for a period of darkness each day as part of a rhythm with a period of light exposure (CIE, 2004/2009), is unchanged. One unspoken problem, however, is the absence of agreement about what constitutes a healthy circadian rhythm: for example, considering only melatonin, at what time ought melatonin to start to be secreted, when ought it to peak, how high ought its amplitude be and when and how fast should its secretion decline? Without agreement about what a healthy pattern should look like it is difficult to evaluate the quality of all but the most dramatically disrupted patterns, or to determine whether a statistically significant effect is large enough to show practical significance.

2.2.1.3 Application tests for circadian regulation. This is a very active area of science, and we are only at the beginning of understanding the complexity of the retinal cellular connections and their contributions to higher brain functions. What are the practical implications of the current understanding? The first consensus report on this subject (CIE, 2004/2009) concluded with five principles of healthy lighting, which included the suggestion that people in industrialized countries do not get enough exposure each day to bright light at the eye, particularly short-wavelength (blue) light. This view is shared by others, notably Lewy (e.g., Lewy, Sack, Miller, & Hoban, 1987) and Foster (2011), whose view it is that contemporary life is lived in continuous biological darkness without sufficient variation in light level or spectral composition to provide the necessary physiological adjustments to the intrinsic circadian clocks.

The first consensus report in this area identified an increased role for daylighting in architecture as a logical application of the evidence (CIE, 2004/2009). Daylight has the characteristics required for proper circadian rhythm regulation (entrainment) for day-active people of all ages: Exterior daylight is intense and rich in short-wavelength radiation in the middle of the day, and becomes less intense, particularly in short wavelengths, in the evening.

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, even likely, that some patterns of light exposure and ways of life leave one in better physical and mental health than others.

The limited evidence available today suggests that in contemporary industrialized countries, average light exposure is less influenced by latitude and climate than one might expect (Table 1), although this is less surprising when one considers the evidence that in both North America and Europe people spend 90% of their time indoors (Klepeis et al., 2001; Leech, Nelson, Burnett, Aaron, & Raizenne, 2002; Schweizer et al., 2007). As seen in Table 1, even in southern California the wintertime light exposures are quite low; at higher latitudes, wintertime exposures are less than half an hour per day – although it is not clear from the currently available data whether the short exposure time relates to the shorter day length at higher latitudes, or to the colder outdoor temperatures, or both.

Table 1. *Average minutes per day while exposed to >1000 lx, by city and season.*

	Measure-ment location	N	Summer	Autumn	Winter	Spring
Bozeman, MT (46°N) (Heil & Mathis, 2002)	wrist	12		36		
Montreal, QC (45°N) (Hébert, Dumont, & Paquet, 1998)	wrist	12	156		24	
Montreal, QC (45°N) (aan het Rot, Moskowitz, & Young, 2008)	wrist	48	91		26	
Montreal, QC (45°N) (Goulet, Mongrain, Desrosiers, Paquet, & Dumont, 2007)	wrist					
Morning types		12	148			
Evening types		12	94			
Rochester, MN (44°N) (Cole et al., 1995)	wrist	24	143		23	
San Diego, CA (33°N) (Espiritu et al., 1994)	wrist	106	130		80	
Zurich, Switzerland (47°N) (Hubalek, Brink, & Schierz, 2010)	spectacles	23				105

Climate-based differences in light exposure are to be expected. The data from Goulet et al. (2007) in Table 1 illustrate the influence of chronotype, a personality difference. People with the morning chronotype (“larks”) show a phase advance and have a preference for early rising. Those with the evening chronotype (“owls”) show a phase delay and prefer to sleep later in the morning. This difference is not merely a matter of personal taste, but has been associated with differences in physiological functioning (Bailey & Heitkemper, 2001; Kudielka, Federenko, Hellhammer, & Wüst, 2006) and can be reliably assessed using standardized questionnaires (Horne & Ostberg, 1976; Smith, Reilly, & Midkiff, 1989). Goulet et al. (2007) found that the people with evening chronotype experienced lower light exposures because they missed some of the bright morning light, although both morning and evening chronotype groups were well entrained to the pattern of light and dark they experienced. Thus, it is not easy to state that a specific time of day is the best time for bright light exposure, as the best time will depend on the individual and their chosen habits.

Occupation and activities are other influences (Dumortier, Nollet, Cooper, & Gronfier, 2007). Hubalek, Brink, and Schierz (2010) found that office workers’ light exposure patterns differed markedly between workdays and days at home; some of the days at home showed very low light exposures. The daily patterns for this sample were quite different from previously reported data for security guards in the same country (Koller, Kundi, Stidl, Zidek, & Haider, 1993).

Only very recently have measurement devices become available to enable naturalistic assessments of the spectral properties of daily light exposures (Gordijn, Giménez, & Beersma, 2009; Hubalek, Zöschg, & Schierz, 2006) and few studies have appeared in the literature. Hubalek, Brink, and Schierz (2010) measured both conventional photometric units and the separate component of short-wavelength light. Among their findings was a high correlation between the conventional visual illuminance and the short-wavelength component; this meant that it was not possible to enter both variables into predictive models for mood and sleep quality

outcomes. In the separate regressions, they found that days with higher total light exposures and days with relatively less short-wavelength light were both followed by nights of higher-quality sleep. The finding for the short-wavelength component was counterintuitive, but probably reflected the fact that the days with high visual illuminance exposure were very high in all wavelengths, so that the overall higher light exposure was more important than the spectral range in which it occurred.

Another possibility concerns the effect of timing, which was not tested with the Hubalek (2010) data. Leppämäki, Meesters Haukka, Lönnqvist, and Partonen (2003) field-tested a dawn simulation device in the autumn and winter in Finland (lat. 60°N), and found that participants' night-time sleep quality improved modestly after six nights of use, and declined after the device was not used. The report did not specify the light source for the simulator, but it was described as providing a slow ramp, over 30 min, from 0 to as high as 300 lx; participants self-chose settings of 100, 200, or 300 lx and the time at which the simulated dawn would start. Apart from the possibility to use an electric light source to signal waking time, the study suggests that a modest increase in light exposure around waking time could improve night-time sleep.

To vary the amount of short-wavelength light exposure, Giménez, Bollen, Gordijn and Linden (2009) provided orange contact lenses to participants to simulate the reductions in total illuminance and short-wavelength exposure that occur with aging. After 16 days with the lenses, participants were sleeping less each night than they had previously, but there were no differences in measures of sleep efficiency or sleep fragmentation. They also found evidence of adaptation. After two days of wearing the lenses, participants showed reduced melatonin suppression response to a night-time bright light stimulus, but this response had disappeared at the end of the 16-day trial.

A few studies have taken the opposite tack, explicitly increasing daytime light exposure. Kaida, Takahashi, Haratani, Otsuka, Fukasawa, and Nakata (2006) examined using naturalistic light exposures through a window, finding that this exposure reduced afternoon (post-prandial) sleepiness. Electric lighting during daytime has also been found to have this effect (Rüger, Gordijn, Beersma, de Vries, & Daan, 2006).

The healthy adults in the previous studies probably experience relatively little of their total light exposures in their homes. Not surprisingly there has been considerable interest in studying populations who spend almost all their time indoors, in private homes or institutions. Among the most robust findings concern light exposure for people with dementia. Night-time sleeplessness and restlessness are particularly serious problems for the patients and their caregivers alike. Field investigations have found that people with low daily light exposure show more disturbed circadian rhythms (Ancoli-Israel et al., 1997; Shochat, Martin, Marler, & Ancoli-Israel, 2000). Ambulatory monitoring of 77 institutionalized elderly people showed that their median daily exposure to light over 1000 lx totalled 10.5 min, and the levels for one-quarter of the sample were so low that they must have spent all of their time in dimly lit rooms (Shochat, et al., 2000). This study found that higher daily light exposure was associated with fewer night-time awakenings.

Attempts to use various light therapy techniques to influence sleep quality of nursing-home patients have tested various light delivery devices, intensities, and times of day. Among the earliest of these investigations was a field trial in which the living room at a nursing home was equipped with a larger number of a higher wattage of fluorescent lamp than it had had previously (Someren, Kessler, Mirmiran, & Swaab, 1997), increasing the vertical illuminance at the eye position of seated participants from a mean of 436 lx to 1136 lx and ensuring a higher light exposure over the entire day. In the intervention period of four weeks, the residents' rest-activity rhythms became more stable, showing less of the night-time fragmentation that is typical of Alzheimer's disease.

This was followed by a randomized field trial with several nursing homes, in which there was an additional (double-blinded) intervention in the form of a night-time dose of melatonin

(Riemersma-van der Lek et al., 2008). Participants in the increased light condition had the possibility to be exposed to 1000 lx (measured at the eye in the gaze direction) of 4000 K fluorescent light in the living room of the facility; those in the dim light condition were exposed to levels closer to 200 lx. The study ran for two years. The results showed that increasing the light level in the living room improved cognitive functioning, mood, and sleep; melatonin also improved sleep but caused mood problems except when administered together with the higher light level. This investigation is the clearest suggestion yet that a higher light level in a residence for the elderly could prove of great benefit.

A somewhat smaller, but also well-designed, field trial showed that an increase in ambient lighting in the dining and activity rooms of long-term-care facilities to 2500 lx (horizontal) led to an increase in night-time sleep for dementia patients if the higher level was delivered in the morning or all day (Sloane et al., 2007). The increase was larger for the patients with more severe dementia.

Other investigators have used light therapy interventions to address sleep and activity problems in elderly patients with various forms of dementia. Mishima, Hishikawa, and Okawa (1998) tested the effects of morning bright light therapy (5000 – 8000 lx, probably measured at the eye, 09H00 to 11H00) on night-time disturbances in patients with vascular dementia and Alzheimer's disease. The light therapy resulted in fewer night-time awakenings for the vascular dementia patients but not for the Alzheimer patients. Koyama, Matsubara and Nakano (1999) found that late-morning bright light therapy delivering 4000 lx at the eye (spectrum unspecified) increased night-time sleep and decreased day-time waking in three participants with dementia, and delayed sleep onset in three other periods. Late-evening abnormal behaviour ("sundowning") was reduced in all patients. Dowling et al. (2008) tested morning (09H30 to 10H30) bright light therapy (>2500 lx at the eye, vs. 200 lx) in a crossover design with melatonin administration in 10-week blocks of Monday – Friday treatments. They found that the combination improved daytime activity and reduced daytime sleepiness, but did not find the expected effects on night-time sleep.

Increased light exposure in the form of 1 hour of exposure in the evening to a 2500 lx white fluorescent light therapy box improved total wake times for Alzheimer's disease patients who lived at home. Increased daily walking was also beneficial (McCurry et al., 2011), as was the combination of light exposure plus walking. In the home setting, adherence to the light treatment was a problem, and those who did not adhere to it regularly did not show as great a benefit as those who did. The benefits were not sustained at a six-month follow-up, likely because the caregivers did not all persist with the intervention.

Figueiro (2008) (or see also the early report of this work in Figueiro (2006)) tested an evening intervention, with light-emitting diodes placed in the field of view to deliver supplemental red or blue light in the evening. She found that the blue light-emitting diode (LED) exposure reduced night-time awakenings but the red did not, which is as would have been predicted based on knowledge of the ipRGC action spectrum for melatonin suppression.

One study tested the hypothesis that increasing the short-wavelength component of the daily light exposure (using a 17,000 K fluorescent lamp as compared to a 2700 K lamp) while keeping the overall illuminance relatively low would result in better circadian regulation among dementia patients attending a day-care centre (Hoof, Schoutens, & Aarts, 2009). The space also had daylight, so the intervention did not result in as clear a difference in light exposures as had been expected. Not only did they not observe the expected benefits, but the 17,000 K condition was considered to be unattractive and undesirable.

Comparisons of the various investigations of light exposure in the elderly are difficult because of the diverse patient populations as well as the diverse times, spectra, and intensities of light used for the treatments. The rigorous Cochrane Collaborative reviews have concluded that there is insufficient evidence to conclude that bright light therapy is effective for managing sleep or behavioural problems associated with dementia (Forbes et al., 2009), but see merit in

continuing investigations with more rigorous methodologies. There is a common theme here in that all of the studies suggest that the light exposures that are experienced by senior citizens, whether in their own private homes or in residential institutions, are very low (Aarts & Westerlaken, 2005; Charness & Dijkstra, 1999; Sinoo, Hoof, & Kort, 2011). This probably explains the fact that beneficial effects have been observed for light exposures at all times of day, so that any regular increase in light exposure would have a beneficial effect on circadian regulation. Although not all studies have observed positive effects of higher light exposures, none have reported serious adverse consequences. It seems likely that increasing the daily light exposure through improved daylighting would result in better circadian regulation than occurs with the continuous exposures in the 200 lx range measured in the ecological (naturalistic) monitoring studies.

At the other end of the lifespan, recent investigations have focused on the light exposures of infants and teenagers. Actigraphic measurements showed that babies are exposed to lower levels of light than adults (median minutes/day > 1000 lx was 18). Those with higher light exposures tended to show stronger circadian patterns (Tsai, Thomas, Lentz, & Barnard, 2011, in press). Caregivers who provide clear circadian signals to their infants might find that their sleep-wake patterns regularize at an earlier age, but this hypothesis remains to be tested with a larger sample.

Teen-age children have delayed sleep; they tend to stay up late and would, if permitted, awaken well into the morning. Modern school schedules generally do not support this pattern, with the results that many people in this age range are sleep-deprived. Figueiro and Rea (2010b) found that the long evenings of spring, in comparison to winter, resulted in teenagers' being exposed to more short-wavelength light and having significantly delayed circadian rhythms. Removing the short wavelength component by day (using orange-tinted spectacles worn from 06H00 to 15H00) for five days delayed circadian phase, as shown by the dim light melatonin onset (DLMO) in intervention studies conducted in the winter (Figueiro et al., 2011) and in the spring (Figueiro & Rea, 2010b), although self-reported sleep quality was not affected in the winter study (Figueiro, Brons, et al., 2011). Turning this pattern around, one sees that improved circadian regulation for this age group might result if their daytime light exposures, particularly to short-wavelength light, were increased, and their evening exposures decreased.

The CIE concluded in 2004 that proper circadian regulation requires both healthy light and healthy darkness, a pattern that greater use of daylight in buildings will support (CIE, 2004/2009). Human activity patterns can disrupt this in undesirable ways. The increasing use of electronic devices, including LED lighting, which have relatively more short-wavelength light in their spectral power distributions than traditional incandescent lighting, has led to concerns that use of these devices in the evening might disrupt sleep (Cajochen et al., 2011; Figueiro, Wood, Plitnick, & Rea, 2011; Gooley et al., 2011; Santhi et al., 2011, in press).

2.2.1.4 Summary: Circadian regulation. Fundamental research into the effects of light on circadian processes has revealed surprising anatomical and physiological processes. There is strong evidence that circadian processes are primarily controlled by a novel photoreceptor with an action spectrum that peaks at a wavelength shorter than any other known photoreceptor, although there is not yet agreement on exactly what that spectrum is. That the classical rod and cone photoreceptors are connected in some way to the ipRGCs appears to be true, but the complete contributions of all cell types to circadian regulation through the integration of polychromatic light signals is not entirely known as yet.

More important for the present review is the evidence that circadian regulation requires both light and dark periods each day. Increased exposure to bright daylight through windows promotes circadian regulation and contributes to good health, as seen most dramatically in the hospital mortality studies. Disrupted circadian rhythms are to be avoided. However, ecological studies show that many people experience very little bright light exposure, and those who are

house-bound or who live in residential institutions experience even less. Without the regular increase and decrease in light exposure there is no signal to which the circadian system can entrain. Consequently, interventions aimed at increasing light exposure for institutionalized dementia patients in general show beneficial effects in the form of increased night-time sleep and reduced agitation. Increasing the morning light exposure of high-school students, together with limits on their evening light exposure to short wavelengths, could help adolescents attend better during school hours and achieve better sleep quality.

Beyond these general statements it is difficult to provide specific guidance. Few studies provide adequate information concerning the light exposure of any participant to permit replication, and the information usually provided is in units suitable to the visual system rather than the circadian system. Moreover, there is no consensus concerning the “normal” (modal or median) pattern for circadian regulation, sleep duration, or melatonin rhythm amplitude against which to assess the practical importance of research results. If researchers report that a given intervention reduces sleep duration by X minutes or changes the melatonin secretion peak by Y per cent, it is not clear whether these outcomes are large enough to warrant a change in practice. Consensus in these areas would facilitate the move from fundamental research to architectural applications.

Despite this uncertainty, it is clear that increased exposure to daylight and sunlight through windows would be an efficient means to provide a higher light exposure in order to promote better circadian adaptation, particularly for those who spend all of their time in their residences (cf., Turner, Someren, & Mainster, 2010). The literature does not show any studies that have tested the sleep, activity, or hormonal effects of an architectural intervention to increase light exposure, making this a clear area of research need. The importance of the timing of the bright light exposure is also not precisely known: if most people would benefit from having this exposure occur as early as possible in the day, rather than later during working hours, this would increase the importance of obtaining that light exposure at home even for those who are out of the house on their working days.

2.2.2 Mood, alertness, and cognition. In addition to light’s role as the regulator of circadian rhythms through the RHT connections to the SCN, light signals pass to a wide variety of other brain structures. We are at the early stages of understanding the function of these signals, disentangling the circadian regulation effects from acute effects on daytime or night-time functioning.

2.2.2.1 Fundamentals. Evidence is mounting that light exposure has an alerting effect that is separate from (and in addition to) the melatonin-mediated circadian regulation system. Night-time exposure to short-wavelength (blue) light, but not long-wavelength (red) light, alters markers of the circadian system, such as melatonin suppression; however, both light exposures influence subjective states of alertness and sleepiness (Figueiro & Rea, 2010a; Kayumov et al., 2005; Plitnick, Figueiro, Wood, & Rea, 2010). Moreover, bright light exposure by day can influence subjective alertness even when there is almost no circulating melatonin (and therefore none to suppress) (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003; Rüger, Gordijn, Beersma, de Vries, & Daan, 2005; Rüger, et al., 2006).

Technological developments in functional magnetic resonance imaging (fMRI) can reveal patterns of brain activity in response to light exposure that were not available to previous generations of researchers. It had long been thought that higher illuminance would promote cognitive performances, but evidence for this effect had been scant. Gifford, Hine, and Veitch (1997) conducted a meta-analysis of investigations into the effect of illuminance on office work performance and reported that there was a modest correlation between illuminance and performance, but that this relationship was attenuated by having an opportunity to adapt to the light level. At that time it was not clear what the mechanism for this effect might be.

fMRI studies have shown that daytime exposure to bright light can increased subjective alertness and enhance activity in the posterior thalamus independently of visual responses; it also can increase activity in the cortical areas responsible for performance on an auditory task (Vandewalle et al., 2006). The ipRGCs are implicated in this process, as blue-light exposure has been seen to contribute more than an equal photon density of green light exposure to cortical activity in a working memory task (Vandewalle, Gais, et al., 2007). Furthermore, the brain areas that are activated by light exposures differ depending on whether the exposure is short or long, and more or less intense, with longer and more intense exposures resulting in longer-lasting brain activation (Vandewalle, Gais, et al., 2007; Vandewalle, Schmidt, et al., 2007). Interestingly, performance on the various tasks was not affected in these fMRI studies, despite the effects on brain activity and alertness. It is possible that either the tasks were not sensitive enough to these changes in brain activities (i.e., they were too easy, or not measured on a fine enough scale), or that longer or more intense exposures are required to produce measurable effects on performance (Vandewalle, Maquet, & Dijk, 2009).

Cortisol, a hormone secreted by the adrenal cortex, regulates metabolism by increasing glucose uptake. It shows a circadian rhythm similar to that of human activity, being secreted when activity levels rise around waking and decreasing as activity slows later in the day (CIE, 2004/2009). Cortisol also is secreted in pulses over the day in response to demanding external events (CIE, 2004/2009). It might be thought that acute light exposure in the daytime should increase activation and result in increased cortisol secretion, but most attempts to demonstrate this have failed (Küller & Wetterberg, 1993; Rüger, et al., 2006). One might think that light exposure at night, which reliably suppresses melatonin, should act as a stressor and result in increased cortisol secretion, but that also has not been observed (Lockley et al., 2006), although some studies have observed light exposure increases cortisol secretion when it occurs in the early morning hours (Leproult, Van Reeth, Byrne, Sturis, & Van Cauter, 1997; Scheer & Buijs, 1999). The challenge in studying cortisol lies in separating the circadian and acute aspects of its secretion, requiring very careful experimental controls. In one study, cortisol secretion was suppressed by light exposure carefully timed in relation to its circadian cycle (Jung et al., 2010). It remains for future research to develop experimental protocols that can elucidate the acute effects of light exposure on this hormone.

The combination of fundamental and applied research available in 2003 led the CIE to conclude that people in industrialized countries would benefit from higher light exposures to improve mood (CIE, 2004/2009). At the time, the mechanism was unknown. Since then, attention has focused on the neurotransmitter serotonin, which appears to be more active when one is exposed to bright light. Serotonin is manufactured in the body from the amino acid tryptophan, which the body cannot manufacture (i.e., it is an essential amino acid); when the body lacks tryptophan, mood tends to decline. Acute tryptophan depletion can be induced by ingesting a protein mixture that lacks this amino acid. The first study to observe the effect of bright light on this system showed that mildly seasonal women (i.e., women whose scores on a personality inventory suggested that they might experience mild, but not clinical, levels of unhappiness each winter) in whom acute tryptophan depletion had been induced showed the expected drop in mood when they were in dim light (10 lx), but not when they were in bright light (3000 lx) (aan het Rot, Benkelfat, Boivin, & Young, 2007). In a later study involving healthy women with experimentally induced acute tryptophan depletion, bright light prevented changes in facial emotion perception that were observed in dim light (aan het Rot, Coupland, Boivin, Benkelfat, & Young, 2010).

Vandewalle et al. (2010) examined brain responses to emotional stimuli using fMRI, comparing the patterns of responses to 460 nm light and photon-density-matched 555 nm light. The stimuli were sentences expressing either neutral or angry emotions (as established by pre-testing) and read by professional actors. Responses to angry stimuli in the voice area of the temporal cortex and the hippocampus were stronger under 460 nm light than 555 nm light, and

the pattern of activation showed stronger interconnections between the voice area, amygdala, and hippocampus as well. The authors suggest that the light signals from ipRGCs are therefore involved in emotional processing, even during daytime. It remains to be seen whether these results and the serotonin metabolism studied by aan het Rot et al. (2007; 2010) are related.

2.2.2.2 Applied research. As noted above, a pattern of research in various settings supports the suggestion that exposure to high light levels (typical of interiors with direct sun exposure or substantial daylight) can have beneficial outcomes for health and well-being. These studies come from a variety of research traditions including epidemiology, exposure monitoring, and experimentation. The original findings of the CIE (2004/2009) have been supported by work published since then.

Among the earlier studies, Beauchemin and Hayes (1996) examined the hospital records for severely depressed individuals whose rooms happened to lie on the sunny or darker sides of the psychiatric wing. Those on the sunny side stayed on average 2.5 fewer days in hospital than those on the darker side. There was no way to ascertain that assignment to rooms had been random, but neither was there evidence of any systematic bias; rooms appeared to have been assigned as they came available. This finding is broadly consistent with a correlation observed by Mathes and Harrison (1981), in which having a sunny dormitory room predicted happiness in university undergraduates. Determining causality is a problem, however, because in both studies the brighter rooms might also have had somewhat better (more attractive and/or more natural) window views.

Hospitals provide many health outcomes and opportunities for naturalistic investigations. Sunny hospital rooms have also been associated with lower cardiac mortality (Beauchemin & Hays, 1998), less post-operative delirium (Wilson, 1972), lower levels of post-operative pain (Walch et al., 2005), and shorter overall stays (Choi, Beltran, & Kim, in press). The strongest of these studies is the one by Walch et al. (2005), which used a prospective design and included measurements of light exposure, showing that patients on the brighter (west) side of the corridor experienced higher light levels and requested less opioid medication for pain relief following spinal surgery while showing the same level of pain relief as the patients on the dim (east, which was obstructed from direct sun) side. The two groups had the same length of stay and rated depression scores, but the bright-side patients reported greater relief from stress at discharge time.

Sunny rooms also show benefits to healthy working people; for instance, Leather, Pyrgas, and Beale (1998) found that the size of the sun patch on an office floor positively predicted general well-being, job satisfaction, and lower intention to quit the job. Boubekri, Hull, and Boyer (1991) found perhaps the only non-linear effect in the literature, a quadratic function in which relaxation increased with sun patch size to a maximum around 20% of room floor area, and then decreased when the sun patch increased further in size. They suggested that at higher levels, thermal comfort or glare discomfort might have outweighed relaxation benefits. Although further systematic investigation is warranted to determine the bounds of the effect, the pattern of results is consistent: Inhabiting spaces where direct sun is possible can contribute to improved physical health. No studies have reported adverse health consequences following occupancy of a sunny room where shading controls could limit discomfort.

Among the investigations leading to the original CIE recommendation was the finding by Espiritu et al. (1994) that San Diego residents who reported lower daily light exposures also reported poorer mood and more atypical depression symptoms. This finding has since been replicated (Jean-Louis, Kripke, Cohen, Zizi, & Wolintz, 2005), with the addition of evidence that the problem of lower light exposure is greater for those with ophthalmic dysfunction. More direct evidence for this relation comes from aan het Rot et al. (2008), who observed positive relations between bright light exposure and both arousal and pleasant mood, using an event-contingent recording protocol that allowed them to connect light exposures and the mood immediately following. Hubalek et al. (2010), however, did not find any correlation between daily light

exposure and daily mood reports, which they attributed to low statistical power and the daily averaging of mood in their protocol.

Two correlational self-report studies, both from large European samples, are consistent with these findings: Grimaldi, Partonen, Saarni, Aromaa and Lönnqvist (2008) surveyed a large Finnish sample from the general population over age 30 and found that self-reported adequacy of interior illumination was negatively related to health-related quality of life scores (that is, people who reported poorer interior illumination levels at home and at work also scored lower on a standardized measure of health-related quality of life). WHO's Large Analysis and Review of European Housing and Health Survey, covering eight cities across Europe, provided the source data for an analysis by Brown and Jacobs (2011), who found that individuals who reported inadequate natural light in their homes were at greater risk for depression and falls.

Conversely, two studies have failed to find simple relations between weather-based metrics of sunlight or daylight availability and depression rates: de Craen et al. (2005) examined depression rates in an elderly Dutch population (over 85 years old), finding no influence of season, sunlight duration, daylight or rain on depressive symptoms; perhaps this is more reflective of the perpetual low light exposures observed in Dutch seniors' residences (Aarts & Westerlaken, 2005; Sinoo, et al., 2011) than a lack of benefit for increased light exposure. Axelsson, Ragnarsdottir, Pind, and Sigbjornsson sought an explanation for the comparatively low rates of seasonal affective disorder in Iceland, noting no correlation between depression and exterior daylight availability (Axelsson, Ragnarsdóttir, Pind, & Sigbjörnsson, 2004b), but finding that year-round the Icelandic sky is more blue than previously thought (Axelsson, Ragnarsdóttir, Pind, & Sigbjörnsson, 2004a), raising the possibility that this results in a greater-than-expected activation of non-visual light-detection processes and a protection against depression.

The effect of lower light exposure might be greater for people with depression than those without. Kent et al. (2009) found that for people with depression, low sunlight exposure (determined from weather data for the area where the individual lived) predicted cognitive impairment; however, there was no relationship between sunlight exposure and cognition for people without depression. Deriving lighting or daylighting applications from this study is difficult in that the index of sun exposure was indirect rather than a local measured exposure. Moreover, this correlational study cannot establish causation.

Experimental evidence bolsters the epidemiological and correlational studies. A Finnish research group has conducted several investigations in which daily light exposures in healthy adults have been increased in various ways during the winter months at a high northern latitude (60°N). Some of these studies supported the development of the conclusions of the CIE report (CIE, 2004/2009), and others have appeared in the literature since its publication. Increasing the light levels (to 2500 – 4000 lx measured horizontally) in a gymnasium led to greater vitality improvements and reduced atypical depressive symptoms for those who exercised there for three one-hour sessions weekly, compared to those who exercised in the regular conditions (400-600 lx horizontal) and to a relaxation training control group (Leppämäki, Partonen, Hurme, Haukka, & Lönnqvist, 2002; Leppämäki, Partonen, & Lönnqvist, 2002; Partonen, Leppämäki, Hurme, & Lönnqvist, 1998); the finding is strongest for people with sleep disturbances (Leppämäki, Haukka, Lönnqvist, & Partonen, 2004). This research group also found that healthy people who used a light box for an hour a day at work or home in the winter showed reduced depressive symptoms during the weeks when the lights were used but not in the off weeks (Partonen & Lönnqvist, 2000).

Ecological studies also suggest that higher light exposures will have beneficial effects on social behaviour as well as mood. Two quasi-experiments conducted in the Midwestern United States showed that helping behaviour improved under sunny conditions compared to cloudy conditions: Cunningham (1979) asked passers-by in a public place for assistance, finding that in both summer and winter the likelihood of receiving the help was greater the more sunny were

the conditions; temperature showed a negative relation to helping in the summer and a positive relation in winter. A second study of restaurant tips found that patrons left larger gratuities on sunny days than cloudy ones; interestingly, the waitresses were also in more pleasant moods on the sunny days, although their moods were unrelated to the size of the tips they received (Cunningham, 1979).

aan het Rot et al. (2008) asked mildly seasonal women to wear an Actiwatch for 20 days, during which time they completed a questionnaire following each social interaction that lasted more than five minutes (this study was also the source of the mood data discussed above and light exposure data shown in Table 1). The social interactions that followed periods exposed to more than 1000 lx at the wrist were reported as being less quarrelsome and more agreeable than those following lower light levels, after controlling for season, day, time and location.

Except for Hubalek et al.'s (2010) exposure study, none of the investigations here have specifically measured the spectral content of light exposures. Those that observed beneficial effects for rooms with windows or sunshine, or that included outdoor exposures can be assumed to have relatively greater short-wavelength exposure than those involving interior electric lighting. Two studies, however, have examined the effects of using a 17,000 K fluorescent lamp on officer workers' well-being. In addition to the sleep findings reported above, both Viola et al. (2008) and Mills et al. (2007) found that participants whose offices used the new lamp showed improved daytime alertness, mood, and general well-being in comparison to those who retained their standard 4000 K lamp, both conditions being equated for illuminance.

2.2.2.3 Summary: Mood and alertness. There is mounting evidence, from high-quality studies, that daytime light exposure has acute effects on mood and alertness that also influence social behaviours and that could influence cognitive performance. The processes by which these effects occur are not yet known, nor is the spectral sensitivity of these undefined systems. However, it does appear clear that increased light exposure would prove beneficial for many people. The ecological studies have primarily tracked working people whose total light exposure occurs in many places; thus the general recommendation that light exposures should increase may be broadly applied to the settings in which ecological measurements occur. These same exposures will produce circadian entrainment whether they occur at home, at school, and work, or during the daily commute; the ideal would be for a regular daily pattern of light and dark. Precisely what the daily light dose ought to be is unknown, as is the question of whether the dose differs for different groups – for example, the very young or the very old.

2.2.3 Summary: Non-visual ocular processes and light through windows.

Many physiological processes show circadian rhythms that are coordinated through pineal melatonin, which in turn is regulated by the daily cycle of light and dark periods. Mounting evidence, all of it from industrialized countries, shows that the daily light exposure of most people is quite low and that increasing light exposure can improve sleep quality. Exactly when this light exposure ought to happen depends on the individual, but in general the best outcomes occur with increased exposures from early morning through mid-afternoon. Other evidence suggests that mental health, general well-being, and social behaviour would also benefit from an increase in daily light exposure. Short-wavelength light appears to be more potent, although all wavelengths have some effect.

Many questions remain unanswered. There is no agreement about the action spectrum for melatonin regulation, and as yet no certainty about the combined contributions of rods and cones and ipRGCs to either circadian regulation or to acute effects such as serotonin activity. Although it is known that these systems respond to the timing, intensity, duration, spectrum and history of light exposure, it is not yet possible to state what constitutes an adequate daily dose of light or dark.

Although no studies have used architectural daylighting to achieve the increased light exposures, one would expect this to be as effective a means to achieve the end as any electric lighting solution, and certainly a more energy-efficient one. It seems likely that daylight provides the intensity, spectrum, and timing required to fine-tune circadian rhythms, but to do so at the same time as providing for the needs of the visual system described above will be a challenge. The mere presence of a window will not guarantee that it or its shading devices will be used in a way that delivers the optimal light dose to the occupant, meaning that further understanding of the activities in residences and of the residents themselves will be necessary.

Because limiting night-time light exposure is also important to circadian regulation, there is also a role for shading and screening devices on windows to reduce light exposures at night. This effect has two directions: to limit the amount of light entering the home from outside, especially in sleeping rooms, and to limit the amount of light shining outside. The latter consideration is with respect both to the possible effects on people in neighbouring residences and the effects on nocturnal organisms.

2.3 Skin Exposure

2.3.1 Thermal sensation. It is trivial to remark that the presence of windows influences the thermal environment in the building and that this influence will depend on the characteristics of the glazing (number of panes, type of glass, use of fill gas or vacuum, type and placement of coatings, etc.) as well as on the size and orientation of the windows. Windows can cause both thermal gains and heat loss, and both will influence the comfort of the people inside, depending on the climate, season, façade orientation, time of day, and use of internal or external shades. These physical variables would be expected to influence the physical conditions inside the building in predictable ways from physics and engineering models. If one accepts Fanger's (1970) predicted mean vote (PMV) model of thermal comfort, based on air temperature, radiant temperature, air movement, relative humidity, clothing and activity level, one could develop a model of window effects on thermal sensation, as has been done (Stavrakakis, Karadimou, Zervas, Sarimveis, & Markatos, 2011).

The PMV model, however, does not take into account human adaptability (Brager & de Dear, 1998; 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 (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.

Neither in work environments nor in homes is there substantial literature on the interactive effects of thermal comfort judgements and visual perception, let alone the interaction between light dose and the thermal consequences of using windows to deliver the dose. The one investigation that emerged from the literature review examined visual and thermal comfort of a factorial design of two room temperatures crossed with three light source types (daylight, electric light, and combined lighting) in an office setting (Laurentin, Berrutto, & Fontoynont, 2000). Illuminance was controlled at 300 lx under all conditions and the room was necessarily climate-controlled to achieve the set temperatures, so this is not a study to answer the question concerning whether thermal gains from daylighting to increase light dose or to increase feelings of spaciousness would be acceptable or not. Nonetheless, it is interesting to note that both the visual and thermal conditions were considered to be more pleasant when the light source was daylight than in the other conditions. This suggests that the tolerance for thermal effects associated with increasing daylight at home might be higher than the PMV model would predict.

2.3.2 Ultra-violet radiation. Electromagnetic radiation penetrates skin — for example, infrared wavelengths give rise to the sensation of warmth. Biologically, the most interesting wavelengths are the very short wavelengths of the ultra-violet range from 280 nm to 380 nm. Skin absorption of ultra-violet radiation initiates several biological processes, several of them unwanted, such as sunburn, the genetic changes leading to skin cancers, and premature aging (Juzeniene et al., 2011; Webb, 2006). However, part of the same spectral range that causes these adverse consequences also results in the production of a necessary prohormone, Vitamin D. Vitamin D synthesis in the skin occurs in reaction to ultra-violet (UV) radiation exposure in the UVB range (280-315 nm) (Juzeniene, et al., 2011; Webb, 2006). Vitamin D can also be obtained through dietary supplements.

Vitamin D has long been known to regulate calcium absorption and to maintain strong bones and teeth (DeLuca, 2004), and in recent years it has been connected to immune regulation (Hayes, Nashold, Spach, & Pedersen, 2003), cardiovascular disease (Zittermann & Gummert, 2010), and mental health (Humble, 2010) and implicated in the etiology of cancers (Grant, 2010) and auto-immune diseases such as multiple sclerosis (Kampman & Steffensen, 2010). For a recent comprehensive overview, see Juzeniene et al. (2011). Although recommendations for healthy vitamin D levels have changed in recent years (Canadian Cancer Society, 2007; Institute of Medicine, 2011), the medical community disagrees as to what constitutes an adequate level of vitamin D to maintain good health and there is additional disagreement concerning the levels that might prove toxic (Heaney & Holick, 2011; Vieth et al., 2007).

With the publication of a new report by the CIE recommending that public health authorities develop recommendations for minimum levels of UV exposure to promote good health (CIE, 2011c), there will no doubt be suggestions that this exposure be provided through interior lighting, either electric or daylight. The CIE recommendation does not, however, support this practice. Based on current evidence the recommendation is for sufficient exposure to maintain an adequate level of circulating vitamin D; this exposure will depend on the individual's skin type and on the latitude and season as well as the weather, but amounts in general to short sunlight exposures of unprotected skin on the face, neck, and hands, followed by protection using clothing, shade, or sunscreens in order to prevent sunburn and other adverse health consequences. The aim is to achieve an adequate level of circulating vitamin D as a result of exposure to UVB radiation while avoiding dangerous exposure to both UVB and UVA radiation (the latter being in the range 315-380 nm), which can cause sunburn and skin cancer (Webb, 2006). UVA in particular is to be avoided as it does not contribute to vitamin D synthesis but does cause sunburn and skin cancer (Juzeniene, et al., 2011).

Occupants who are unable to go outside (e.g., the elderly or the housebound) might be thought to be good candidates for using windows to deliver an increased UVB dose to promote vitamin D synthesis, but this is not practical. Commonly used glazing units with low-emissivity coatings (used to improve their thermal performance) have a sharp transmissivity cut-off below 400 nm and absorb almost all of the incident UV radiation below 340 nm (in the middle of the UVA range) (DiLaura, Houser, Mistrick, & Steffy, 2011). If one changed the glazing properties to admit more UVB radiation one would expose those same occupants to the risk of sunburn and skin cancer, which would not be sensible. Nor would occupants be pleased with the fading of dyes and degradation of fabrics that would result. Moreover, there is seasonal variability in the UV component of solar radiation that limits the possibility for vitamin D synthesis in the winter months as a function of latitude (Engelsen, Brustad, Aksnes, & Lund, 2005; Krzyścin, Jarosławski, & Sobolewski, 2011); even if one changed the glazing properties there would be many places and seasons where there would be no UV radiation to transmit. Vitamin D synthesis is a beneficial effect of a limited amount of exposure to sunlight, but not a benefit to be delivered through windows.

3. Building Science

Having concluded that windows and view deliver many benefits to people in their homes, it might seem simple to say "provide more!" in order to ensure that residents have the best opportunity to receive those benefits. This section of the report concerns some of the building science issues that require attention in order to deliver the benefits of windows, daylight, and view in a particular building, taking into account other important aspects of design, construction, climate, sustainability, and human needs.

3.1 Daylight calculations

The degree to which the occupants of a residence will experience the benefits of daylight and view through its windows will depend on several factors including, of course, the architectural details of the building. In recent years, as computing power and the availability of reference data for various locations have both increased, it has become possible to develop more sophisticated predictions of the daylight available in buildings than the historic daylight factor (DiLaura, et al., 2011; Reinhart, Mardaljevic, & Rogers, 2006). Collectively these methods have been labelled *climate-based daylight modelling* (Mardaljevic, 2008) in that they use specific local information about daylight from weather stations (detailed measurements over a full year) as input to simulations of lighting quantities in the target building.

Because simulations can deliver many possible outputs, several metrics can be calculated to summarize these data, and as yet there is no consensus on the single best one to use (DiLaura, et al., 2011). Some of the proposed metrics include daylight autonomy (DA), which is the percentage of the year when a target illuminance can be maintained by daylight alone (Reinhart, et al., 2006) and useful daylight illuminance (UDI) (Nabil & Mardaljevic, 2005). Notably, all metrics based on conventional photometric quantities (whether luminance or illuminance) will deliver information about light that is useful for vision, because conventional photometry is based on the V_λ spectral sensitivity function.

UDI is conceptually similar to DA, but is expressed in illuminance bands (e.g., initially these were < 100 lx, 100 – 2000 lx, and > 2000 lx). The value for very high UDI (e.g., UDI>2000 lx) can provide information about the possibility that illuminance levels could cause both excessive thermal gains and glare, both of which could lead to occupant discomfort. The values for the cut-offs are changeable; the initial values were based on the literature and the authors' judgements (Nabil & Mardaljevic, 2005). This flexibility will make it possible to adapt the metric as further information about, for example, glare, becomes available; on the other hand changing the bands will make it more difficult to compare from one investigation to another. Whereas Reinhart's DA approach (Reinhart & Voss, 2003) incorporates a model of user-operated blinds in its calculation, UDI requires a second pass, applying a correction factor based on assumptions about the shading device to the times when UDI exceeds the upper limit and then re-calculating the UDI values accordingly (Nabil & Mardaljevic, 2005).

The movement towards sustainable architecture has driven much of the development of dynamic daylight calculations and software tools for architects, such as DAYSIM (Reinhart & Voss, 2003) and Lightsolve (Pechacek, Andersen, & Lockley, 2008) and associated visualization methods (Kleindienst, Bodart, & Andersen, 2008). These methods are aimed at any building type but are largely driven by the needs of commercial buildings, for which architects and engineers are always engaged and for which the economics justify the time and cost of detailed analyses. Consequently, these approaches have had relatively little application to residences as yet, except for the reports by Mardaljevic for VELUX (Mardaljevic, 2007; Mardaljevic, Andersen, Roy, & Christoffersen, 2011) and one conference paper (Gochenour & Andersen, 2009).

The first of these (Mardaljevic, 2007) evaluated the effects of two building types, and varying window configurations and external obstructions, in eight orientations for six European

climate zones. UDI was the principal metric used as the basis for conclusions. For the residential application, Mardaljevic changed the cut-off values for UDI bands to distinguish between periods when supplementary light might be added (workplane illuminances between 100-500 lx) and when it was thought that daylight alone might be used (500 – 2500 lx). The higher upper limit, 2500 lx, was assumed based on the expectation that people will be more glare tolerant at home than at work. Among the key issues relevant here are the finding that climate and building orientation are the most important contributors to UDI; also not surprisingly, adding skylights decreased the value for the lowest UDI band, (UDI<100 lx) and slightly increased the value for the highest band (UDI>2500 lx). Perhaps most importantly, the investigation demonstrated that UDI predictions require specific calculations for building design, orientation, and climate. Design decisions about building design features, if they are to be made based on predictions of light available for vision, cannot be generalized from studies in a different location or orientation.

The more recent VELUX work extended the 2007 analysis to predictions of light available to the circadian system (Mardaljevic, et al., 2011). This incorporated a model for the assumed circadian effectiveness of a light stimulus that had been previously developed by Pechacek, Andersen, and Lockley (2008) and adapted the simulations to create a prediction of what they called “non-visual effect” (N-VE) with a ramp function between 0% N-VE at 210 lx of D55-equivalent vertical illuminance and 100% at 960 lx. The authors also developed a novel graphical representation of the results that reveals the time-of-day pattern in the availability of a given degree of N-VE in a specific room location and gaze direction. The results, applied again to a set of simulations for varying house design and orientations in varying European climate zones, show the value of the graphical technique as a tool to facilitate comparisons between varying design options.

The principal value of the Mardaljevic et al. (2011) work is to provide a framework in which to understand and to communicate the potential for a given building design to deliver a target light dose. There remain many questions concerning the non-visual ocular effects of light that once answered might change the N-VE function and its conversion to a particular spectral function, but the fundamental framework and the graphical technique for the presentation of cumulative data would remain intact. Among the issues these authors themselves have acknowledged is the identification of the balance point between the delivery of valuable light for both circadian regulation and acute non-visual ocular benefits as against the prevention of discomfort from glare and thermal gains. The present work also did not include a secondary analysis to incorporate any model of shading device use and therefore could be considered to report an idealized view of the maximum possible light dose rather than the realistically achieved doses.

Agreement concerning which daylight calculations to use is becoming an urgent need, but the principal push comes from energy regulations applied to commercial buildings. In North America, energy codes and standards have begun to require the use of daylight harvesting (American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), 2010, 2011; California Energy Commission (CEC), 2008; Canadian Commission on Building and Fire Codes (CCBFC), 2011; International Code Council (ICC), 2009), and some specifically require the use of daylight (California Energy Commission (CEC), 2008). In Europe, lighting energy use in commercial buildings is limited by the CEN standard 15193:2007 (European Committee for Standardization (CEN), 2008) but the lighting conditions provided must also conform to CEN 12464-1 (CEN, 2011). The latter document recognizes the importance of daylight as a light source but does not require its use. Discussions concerning a possible European daylighting standard are ongoing.

Daylighting requirements for residential buildings vary internationally. There are no North American code or standard requirements for daylight in residences. Indeed, the National Building Code of Canada permits windows in residences to provide non-heating-season

ventilation and requires a minimum size for bedroom windows to provide means of emergency egress or – in larger buildings – access for emergency personnel, but does not recognize light admission or view as being related to the code objectives (CCBFC, 2010). The importance of daylighting for Canadian homes might increase with the publication of the energy efficiency provision in Part 9 of the 2010 National Building Code of Canada, which are expected to be published as interim changes late in 2012. The building energy regulations (including electric lighting systems) in California Title 24 apply to residences but do not specify daylighting requirements (CEC, 2008) (although there are requirements for daylighting in non-residential buildings). In Europe, most countries require daylight in houses, but the specific requirements vary. Some building standards set requirements for the minimum/maximum size and/or performance of daylight openings (e.g., sunlight duration), distance between buildings and/or view out; a few set specific daylighting criteria (e.g., daylight factor). However, the nature of these requirements is generally crude and the specifications are not comparable between countries or regions (Tiimus, 2007; Visscher & Meijer, 2006).

Establishing common climate-based daylight calculations and standard levels to be met by new buildings would facilitate the development of design solutions for specific locations that would enable an effective balance between lighting energy savings and building thermal performance. Practical indicators and daylighting metrics specific to residential applications should also be considered and addressed.

3.2 Thermal, ventilation, and energy-use considerations

Providing more access to windows and view in dwellings will necessarily change the thermal performance of the building. The exact change and its consequences for whole-building energy use will depend on the precise glazing choices, shading devices, climate, and orientation, and on the heating, cooling, and ventilation systems and their usage. Moreover, selecting the location and size of opening window units will also depend on achieving desired airflow both for space conditioning and indoor air quality (Stavrakakis, et al., 2011).

From a thermal performance perspective, windows can provide free heating from solar gains in winter, but can cause an energy-use penalty during the summer season if the heat gains lead to increased use of air conditioning. From a lighting perspective they might reduce energy use if they reduce the duration of electric lighting use; this will also depend on the use of shading devices such as curtains or blinds. As discussed above, there exists limited data from office settings on this question but there are no field data concerning switch-on likelihood or shading device use in dwellings. This is a clear gap in our knowledge.

The literature shows relatively little cross-collaboration between the communities that perform daylight modelling and those engaged in thermal and whole-building energy models. This review found one exception, a study of commercial high-rises in Hong Kong (Chung, Kwok, & Mardaljevic, 2010). No studies to date appear to have combined these efforts to study residential buildings.

Better integration between these communities — perhaps initiated through the International Building Performance Simulation Association (IBPSA) — would be valuable. As the building industry develops new materials and designs with the goal of achieving energy neutrality (net-zero energy consumption), the demands for energy efficiency and even electrical generation will require choices that balance providing more access to light and view against insulation, shading, and electrical generation. National and international codes, standards, regulations and recommendations are likely to reflect these competing demands, but in the first instance all will require better understanding and knowledge of these issues derived from sound, peer-reviewed, scientific evidence.

3.3 Fire safety

Building codes regulate the openings in buildings not only to provide light and ventilation, and sometimes to achieve energy targets, but they also have requirements for fire safety. In Canada, for example, the National Building Code limits the percentage of the façade on which openings are permitted as a function of the distance to the neighbouring building as a protection against fire spread (CCBFC, 2010). These limits apply unless there is supplementary fire protection, such as a fire screen. Developing specific designs to deliver access to view or additional daylight will need to take into account these location-specific requirements, which adds to the complexity of the choices and further emphasizes the value of modelling programs to facilitate the comparisons between options.

3.4 Economics

Boyce, Hunter et al. (2003) observed that although providing windows in commercial buildings adds to their cost, they also contribute to the building's real-estate valuation and to the rent that may be asked. One would expect the same to be true of residential buildings — that improving the quality of the light should increase its value. Economists who study real estate use what they call *hedonic models* to analyse the factors that explain real-estate valuations (Gao & Asami, 2001; Kumagai & Yamada, 2008; Samaha & Kamakura, 2008). Although we did not conduct an exhaustive literature search for hedonic models of house prices, few investigations appeared to have included subjective assessments of architectural quality as a predictor (Wilhelmsson, 2002), and none appear to have included objective measures of windows or daylight as predictors. Neighbourhood predictors that are relevant here include access to green space (Gao & Asami, 2001; Kumagai & Yamada, 2008) and sunshine hours (Gao & Asami, 2001), both of which are positively related to housing prices in Japan. A better understanding of how people value windows, view, and daylight in homes in an economic sense would help in the evaluation of the trade-offs between additional windows to provide view and daylight, versus the additional building and operating costs.

4. Summary and Research Directions

Overall the literature is clear that windows and skylights confer many benefits to home occupants, and these occur simultaneously through physiological and psychological mechanisms. The benefits accrue through both access to a view and to the possibility for increased daylight exposure. The benefits, however, require balance against the potential for adverse consequences such as visual and thermal discomfort at the individual level, and energy and environmental consequences at the building level. Each area reviewed here has gaps and limitations in its knowledge base that suggest both fundamental and applied research questions. Moreover, the compartmentalization of disciplines has largely prevented integrated research approaches that would facilitate the development of more comprehensive models and practical applications.

Table 2, on the following pages, summarizes the literature review in terms of what is known generally and for the specific instance of residential settings. Research questions are presented separately for the general case (usually involving fundamental knowledge) and for residential settings specifically. Following the table is a short list of the highest priority research questions.

Table 2. *Summary of knowledge and research questions, for general knowledge and residential applications.*

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
2.1.1 Visual performance	• Visibility is governed by task contrast, task size, retinal illuminance. • Age is a powerful moderator. • Spectral influence on acuity might favour daylight as a source. • Stray light can reduce visibility, especially a problem for older people.	• All fundamental vision findings apply to residences. • Residential light levels are generally lower than illuminance recommendations for vision, especially for the elderly.	• Vision science evidence uses strong research methods. There are few open questions about achromatic visual performance at photopic levels. • Age-related reductions in visibility because of glare can be predicted well.	• Visual performance models do not address chromatic tasks. • There is limited data for people with low vision.	• What is the visual performance of people under naturalistic conditions? Are the levels really acceptable, even if they are lower than recommended practice? Would better daylight (including appropriate means to prevent glare) improve visual performance? • Why do people choose low levels in their homes? What are the factors that keep them from making more or better use of daylight to meet their visual needs?
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.	• Living rooms look more spacious, beautiful, and inviting with windows. • Larger and more transparent windows and skylights are preferred in living and dining rooms and kitchens; privacy leads to smaller and fewer windows desired in bathrooms. • Cultural factors and room functions influence window preferences. • No specific data exist for the preferred degree of opening for residential rooms. • Glazing modifies the light admitted, and this influences spatial appearance; greenish tints are undesirable.	• 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. One study from 1973 in UK offices is too limited a data set on which to base residential recommendations that could apply across cultures. •	• 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?	• Where in the dwelling do people want windows? How large and where should they be located in the space? What factors other than light and view influence window preferences? For instance: privacy; wall areas for other functions (display, storage); hobbies and tasks requiring darkness; and, prevention of veiling luminances on key surfaces could all influence these choices. • Are there limits to the desire for feelings of spaciousness in residences? What are the cultural or social influences on these desires? • Does the view from the window influence the space appearance, and in turn is this an influence on desired window size and other characteristics? • What is the contribution of spaciousness to overall judgements of housing quality? •

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
2.1.3 Discomfort	• 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 nature and quality of the view. • There is limited data concerning the use of shading devices in offices to prevent discomfort.	• There is no specific model concerning glare in residential settings, neither when the source is electric lighting nor for daylight. • There is no data concerning the use of shading devices in homes to prevent discomfort, but there is anecdotal evidence that this is not the only reason for shades to be drawn. • The available evidence from scale model studies reveals a paradox: the glazing conditions that are perceived as giving the best spatial appearance also give the worst discomfort.	• 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).	• What predicts the lighting conditions at home that cause visual discomfort? • What are the interactive effects of visual and thermal sensations relating to comfort and discomfort? • When do residents close their shading devices? Why do they close them? What effect does this have on the light dose received? What are the consequences for electric lighting energy use? • Could automatic controls for shading devices assist in achieving a healthy balance between light exposure and discomfort prevention?

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
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.	• The results have been consistent for hospital, classroom, and residential settings and across age groups.	• 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.	• What is the restorative value of view attractiveness separately from its nature content? Although difficult to control in existing neighbourhoods, this could influence community planning decisions. • Does the availability of restorative views contribute to a healthier light/dark pattern through increasing light exposure? (i.e., Do people increase light exposure because they look outside more when the view is attractive or of nature?) • Does view quality and content influence shading device use, and if so what are the consequences for light exposures and discomfort?

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential

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.
		• Higher daily light dose contributes to better sleep quality.
		• There is some evidence that for healthy people, the light dose is best delivered earlier in the day.
		• For the institutionalized elderly, daily light exposures are often extremely low. Increasing exposure can improve sleep and circadian regulation.
		• Exposure to gradual dawning (through window or through simulation) can improve sleep quality ratings and morning alertness.
		• Short-wavelength radiation from common luminous devices in the evening affects melatonin secretion and sleep quality.
			• 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 nor of sleep/wake patterns. This makes it difficult to establish the practical significance of statistically significant results.
				• Exactly what is the action spectrum for circadian regulation? Several curves have been empirically reported (Brainard & Provencio, 2006). Some authors base their predictions on action spectra peaking around 460-464 nm (Brainard, Hanifin, Greeson, et al., 2001; Thapan, et al., 2001); others argue that the correct curve is one peaking at 480 nm (Al Enezi et al., 2011; Foster, 2011). 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 (Güler et al., 2008; Lall et al., 2010)?
				• How dark does the dark period need to be, in counterpoint to the light exposure?
					• Taken overall, what are the effects of varying levels of daytime light exposure on healthy populations? Does daily life in the industrialized world generally leave us in perpetual biological darkness? What would constitute a healthy light/dark exposure pattern (light dose), in terms of the spectrum, intensity, duration, timing, and pattern of exposure?
					  • Healthy in this context includes not only outcomes related to sleep quality and circadian regulation, but also task performance, social behaviour, mood, and overall subjective well-being and health status (see section 2.2.2).
					  • Does this pattern differ for various personality types (e.g., chronotypes)?
					  • Does it vary across the life span?
					• Understanding the time-space use in residences would help in understanding where to place design features to achieve the healthy light/dark pattern. These patterns are probably culturally different both at the national level and for sub-populations.
					  • Where in the dwelling do people spend their time when at home?
					  • Which populations spend the most time at home and therefore might benefit most from obtaining light exposure through design features?
					  • In any given room type, what proportion of the time is spent in various orientations and at varying distances in relation to the façade? Do people orient themselves towards the façade?
					• Light hygiene: what do people understand about the effects of light on their health and well-being? Why do they not self-select conditions that would be good for them? How can we promote healthy light hygiene? For example, are there design features that could encourage healthy light exposure (Gochenour & Andersen, 2009)?

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
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.	• Ecological studies of light exposure show high variability during days spent at home, apparently a function of self-selected activities. • General findings of mood and social behaviour derive from light exposures in many settings, including homes.	• 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?	• Would higher daytime light exposures at home improve mood and social behaviours in families? • Could the absence of good daylight be a risk factor for well-being that is more likely in homes of those with lower socioeconomic status? Could we use better daylighting in homes as one way to improve housing quality, particularly in social housing?

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
2.3 .1 Thermal sensation	• Windows and skylights influence thermal sensations, but human adaptability makes the acceptability of conditions difficult to predict. • It is not known whether the change in thermal conditions that accompanies changes in view or daylight would be acceptable.	• There is a total absence of research on the interactive or combined effects of thermal sensation and visual sensations associated with windows, daylight, and view in homes.	• 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 populations will be needed.	• Some populations are likely to be more sensitive to these tradeoffs than others. One might expect adaptability to be lower in the elderly and those who are ill or housebound.

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
2.3.2 Ultra-violet radiation	• 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 sun in the summer show signs of vitamin D insufficiency. This might place them at risk for immune dysfunction and some internal cancers.	• UV exposure requires time outdoors. There is no meaningful possibility of increasing healthful UV through windows or daylight.	• 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.	• 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.	• Designs that facilitate time spent outdoors in sunny weather, particularly for those whose mobility is limited, would contribute to healthy vitamin D status.

Section	General findings	Residential findings	Strength of information / research design issues	Open questions - general	Open questions - residential
3. Building Science	• Architectural modelling tools together with geographic information about solar radiation permits precise measurements of daylight in specific building designs. • Similarly, whole-building thermal performance and energy use can be modelled. • Choices about window size and location also depend on regulations aimed at providing adequate fire safety, sound transmission control, ventilation, and other concerns.	• A method for predicting light exposures for circadian regulation has been developed, based on simulations of residences in several European locations.	• The simulation tools are reasonably well-developed and robust. • Predictions of light exposure for circadian regulation depend on many assumptions about the dose-response relationship, timing, and spectral effects; these are weak because the fundamental photobiology is still under development. • Few studies have attempted to simultaneously predict the light exposure, thermal conditions, and energy use, and none appear to have done so for residences in any climate.	• Common agreement is needed on the most useful climate-based daylight metrics; this should be setting-independent. • Photobiologists need to come to agreement on the healthy light/dark pattern so that simulations can accurately predict the architectural features that will deliver the desired pattern.	• To what degree does the spectral content of the daily exposure vary geographically? Is it necessary to take this into account in predictive models? • How can we convert the healthy light/dark pattern to practical recommendations, including the use of this information in climate-based daylight metrics (Mardaljevic, et al., 2011)? • What are the consequences of this healthy pattern for residential design? For example, if early-morning light exposure is a critical period, ought that to influence the preferred orientation of sleeping rooms to facilitate awakening? • Can architectural simulations accurately predict residential light exposures for well-being (through circadian regulation, alertness, and vision)? Similarly, can they predict conditions that will lead to visual discomfort and help to identify design solutions that will limit discomfort while supporting healthy light exposure? • What are the prospects for integrated modelling approaches that combine daylight models with thermal, ventilation, and energy models? • Are there conflicts between using windows to provide daylight, view, ventilation, thermal control and limits on fire safety; and if so, are there technologies or design approaches that could permit a better balance? • What is the economic value to homeowners of improved space appearance, improved view, better daylight availability, better glare or thermal control?

As the preceding table shows, there is no shortage of research questions facing photobiologists, psychologists, architects, lighting designers and others in the broad lighting community, whether their interests are general or specific to daylighting for residences. The field may be broadly summarised as follows:

1. Human well-being relies on regular exposure to light and dark each day.

2. Daylight is the most energy-efficient means to deliver the light exposure, when it is available.

3. Uncontrolled daylight also can cause problems: veiling luminances that reduce visibility, visual discomfort, thermal discomfort.

4. 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.

5. 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.

6. 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.

7. Using daylight to deliver useful light is sustainable only in concert with the effects on the building envelope, ventilation, and overall energy balance. These require climate-based and locally specific solutions that respect other building system considerations and regulations.

From this analysis flow the following three top-priority research domains:

- **Establish the optimal daily pattern of light and dark exposures for good mental and physical health.**

What is a healthy pattern of light and dark each day? How high should the intensity be in the light period and how low must it be in the dark period? The broad range of environments that humans inhabit demonstrates our ability to adapt to many conditions; how much better might we feel, how much more energetic and vital might we be, if we experienced a more suitable pattern?

- **Determine how our homes 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.**

How will the healthy pattern be experienced in a given residence? We need to understand when daylight can lead to veiling luminances and discomfort and in turn when and why occupants will use shading devices. These inputs can modify the results of simulation runs to provide more accurate assessments of the likelihood that the desired exposure will occur. They also can inform public information campaigns to teach about how to use daylight to achieve proper light hygiene. Technological developments to provide suitable degrees of automation might also result.

- **Develop design solutions and technologies for different climates that deliver healthy light, warmth, view and fresh air with the minimum of energy use.**

The design solutions need to take into account broader issues of sustainability, with daylight predictions occurring hand-in-hand with ventilation, thermal, and energy use modelling so that the resulting architectural solutions achieve a suitable balance between these domains.

5. Concluding Remarks

A famous aphorism has it that we are as dwarfs standing on the shoulders of giants.* This is certainly true of the present topic. The lighting community has been trying to integrate these issues for more than thirty years. Many of the topics reviewed here were discussed at a CIE symposium on daylight held in Berlin in 1980 (Krochmann, 1980) and at a workshop held by Health and Welfare Canada in Ottawa (HWC) in March 1980 (HWC, 1980). Progress has been made: In Ottawa there was extensive discussion of the purposes of windows and some uncertainty that the psychological and health benefits attributable to daylight and view were more valuable to humanity than the energy savings possible with sealed, insulated solid walls (HWC, 1980). The literature reviewed here demonstrates clearly that windows confer benefits by delivering daylight and view. The late Prof. Eliyahu Ne'eman suggested at the close of the CIE event that it would be worthwhile to compile climate data about daylight from around the globe (Krochmann, 1980): Thanks to initiatives such as the International Daylight Measurement Year of 1991 (http://idmp.entpe.fr), we have the climate data to support advanced modelling to predict daylight quantities and lighting energy savings achievable by various architectural choices.

Nonetheless, there remains much to be done before we will understand well enough the roles of windows in our lives. In 2005 the WHO Regional Office for Europe began a series of meetings of technical experts to discuss disease risks associated with inadequate housing. The panel at the initial meeting concluded that there was inadequate evidence to assess risks associated with light exposure (WHO Regional Office for Europe, 2006). Consequently, lighting was not included in the comprehensive report on the environmental burden of disease associated with inadequate housing that resulted from this project (Braubach, Jacobs, & Ormandy, 2011).

Not all of the needed work is new research. The job of integrating knowledge is greatly complicated by the inconsistent reporting of information and poor research design and analysis. Thus, common standards of several kinds are also needed:

- Agreement on reporting requirements to describe light exposures, to facilitate comparisons between studies. Such standards might use a new photometric quantity based on a spectral sensitivity function, or might be based on agreement to report the spectral power distribution of light sources together with an intensity metric and information concerning the duration and timing of exposure, and ideally the light history or pattern.
- Agreement on reporting details of experimental methods and statistical analysis, together with rigorous application of appropriate methods from the relevant scientific and engineering disciplines. Here too, inadequate information makes it difficult to evaluate the quality of research results and almost impossible to conduct meta-analyses to form generalized conclusions (Gifford, et al., 1997).
- Agreements to share data for secondary analysis, where participant confidentiality and

* "*Bernard of Chartres used to say that we are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size.*" (John of Salisbury, quoted on Wikipedia at http://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants)

anonymity can be preserved. International organizations such as DataCite (www.datacite.org) exist to promote and support data archiving, and some nationally-funded research agencies mandate this for projects they have supported (e.g., in the USA, the National Institutes of Health, http://grants.nih.gov/grants/policy/data_sharing/).

It is time for this generation of researchers to discover for itself the collaborative and co-operative spirit of the giants before us, to develop the necessary consensus documents that will support those who come after.

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