Building and Environment 70 (2013) 138–149

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Modelling ‘non-visual’ effects of daylighting in a residential environment

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ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form
12 August 2013
Accepted 14 August 2013

Keywords:
Daylighting
Circadian
Non-visual effects
Health
Residential
Building simulation

ABSTRACT

The importance of light not only as a therapeutic tool but as an essential element of healthy living has been highlighted by the recent discovery of a specialized photoreceptor in the eye responsible for synchronizing our internal circadian pacemaker. This pigment, melanopsin, differs from visual receptors in several characteristics, here simplified into a blue-shifted spectral sensitivity and a dose–response curve established from night-time studies. While a vast range of tools has been developed to simulate the amount of light in lux or lumens falling on a static, horizontal surface, corneal exposure estimates are needed for modelling the biological responses to light in space, which require a vertical sensor that can rotate and translate as a human eye does. This paper examines the effects of housing design upon the amount of daylight available for maintaining synchronization of the human circadian system considered in conjunction with human movement, using historic Boston row houses as a case study. Based on a series of simulations taking into account the two above-mentioned characteristics of the non-visual system, this paper proposes a preliminary workflow for suggestions regarding lighting restoration and opens new perspectives on future variables to include. This study found that even modest renovations like painting the space a lighter colour have a noticeable impact on the light received by a moving sensor. More aggressive design choices, such as not using the basement floor of the house for apartments, raise the amount and timing of light received to nearly the level of the best-case scenario.

1. Introduction

New design paradigms which seek to improve human health and well-being must address issues of historical conservation and energy consumption if they are to be widely adopted, financially viable and practical. Many high-density cities contain buildings from various eras which contribute to a vibrant urban texture. Furthermore, restricting new construction by reusing old structures and reducing the materials used for building is an important step toward energy usage reduction. For both of these reasons, it is important to consider whether existing structures can be adapted into liveable residences or working places.

Light has a number of circadian, neuroendocrine and neurobehavioral effects in addition to permitting vision, and consideration of these effects is of increasing importance in architectural and lighting design [1]. Architecture provides the interface between the external environment and the human body, it therefore mediates how humans access light. Light is the primary time cue for synchronizing our internal circadian (~24 h) clock with the environment. The circadian pacemaker is an internally generated oscillator with a period that runs close to, but not exactly 24 h, on average 24.2 h [2]. The circadian system controls the timing of many aspects of physiology, metabolism and behaviour including production of some hormones, temperature regulation, sleep-wake cycles, and alertness and performance patterns [3]. In order to ensure correct alignment of physiology with environmental time, the circadian clock is reset on a daily basis to the 24-h light–dark cycle. This light information is detected exclusively by the eye primarily via specialized melanopsin-containing retinal ganglion cells that are anatomically and functionally separate from the rods and cones required for vision, and are most sensitive to short-wavelength visible blue light [4]. Failure to maintain exposure to a robust daily 24-h light–dark cycle causes desynchrony between the circadian system and external time, leading to insomnia, excessive sleepiness, metabolic disorders and increased risk of

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0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.08.018

cardiovascular disease, diabetes and some types of cancer [5]. Shift-Work Disorder and Jet-Lag Disorder are common examples of extreme circadian rhythm misalignment but even small day-to-day changes in light exposure are likely to have undue biological effects [6]. Failure to receive this light information at all, as exemplified by totally blind subjects, results in desynchronization of the internal clock from the 24-h world and development of a highly disruptive condition called non-24-h sleep-wake disorder [7].

Light also has a number of direct acute effects on physiology and behaviour. At night, light suppresses nocturnal melatonin production, elevates heart rate and temperature and alerts the brain [4,8–10]. Daytime light exposure also induces alerting responses, as measured with subjective alertness, improved performance and activation of brain areas involved in alertness, memory and mood [10–13]. Under real-world conditions, exposure to more robust light–dark cycles has been shown to be associated with better workplace performance [14,15], better patient outcome in hospitals [16–18] and more recently, improvements in cognition and reduced depression in dementia patients [19]. While most of these studies have used electric lighting to achieve the effects, natural light–dark cycles are best suited to achieving the timing and spectrum needs for circadian entrainment while remaining within visual comfort levels, and can bring with it substantial energy and cost savings over electric light.

A number of properties of light are important when considering their 'non-visual' effects including light intensity, timing, spectrum, exposure pattern and light history. The circadian photoreception system is extremely sensitive down to room levels of light, particularly during the night. For example, room light exposures in the late evening (~90 lux) will cause significant suppression of melatonin [6]. The melatonin suppression and circadian phase-shifting responses saturate at about 500 lux of light from ceiling-mounted cool white (4100 K) fluorescent lamps, and the associated decrease in sleepiness at night appears to saturate at a slightly lower intensity, ~200 lux [8,20]. Dose–response functions for the alerting effects of daytime light are not currently available but are likely to be similar.

The timing of light is very important. Light exposure in the late evening (~18:00–6:00 h) will delay the timing of the circadian pacemaker, and early morning light will advance it (6:00–18:00 h) according to a Phase Response Curve [21,22], with maximal effects in either direction occurring close to the 'cross-over point' between the direction of shift around (~3:00 h and 9:00 h, respectively, for delays and advances). The timing of light or light avoidance for alerting responses is also important – morning light exposure may be useful in alleviating the sleep inertia i.e. the grogginess experienced when waking [23] – whereas evening light exposure may alert the brain at an inappropriate time and disrupt sleep [24].

Light spectrum has received a lot of attention recently (for review see Ref. [25]) driven by the discovery of a non-rod, non-cone photoreceptor system in the mammalian eye [26,27], including humans [28,29]. Melanopsin is most sensitive to short-wavelength blue visible light (λ_{max} ~480 nm) which matches the action spectra for a number of 'non-visual' responses to light including melatonin suppression and pupillary reflex [29–32], and explains the short-wavelength sensitivity observed for circadian resetting and alerting responses to light [33,34]. More recently, it has been discovered that rods and cones also contribute to these responses, especially at low light intensities and for short-duration exposures [35,36], and therefore the spectral sensitivity of these light responses is a dynamic property, changing depending on intensity, duration and light history.

Architecture becomes an important component in this discussion when one realizes that these vital components of daylight – intensity, timing, and spectrum – are mediated by the form of surrounding structures whose design can have important consequences on the timing and synchronization of circadian rhythms [37]. This is particularly true when we consider that Americans – for instance – on average spend about 90% of their waking hours indoors [38] and are often not exposed to very robust light–dark cycles [39,40]. Increase in distance from a window, and therefore a decrease in the amount of daylight exposure, has been linked to a decrease in productivity and higher absenteeism in the workplace [41]. On the other hand, the introduction of high correlated colour temperature (CCT) fluorescent lamps into an open-plan, daylit workplace improved subjective measures of performance, sleep and productivity [15].

While the workplace is an important component in daily life, the home is as important in the regulation of circadian rhythms, since this is where almost all sleep, and therefore almost all of the biological night, when the body is most susceptible to circadian phase-shifting light, occurs. This paper proposes a lighting simulation framework aiming to start addressing how 'circadian lighting potential' can become part of housing design or renovation processes, using Boston row house apartments as a case study. As a proof-of-concept, it examines the relative impact of a range of design factors in achieving "sufficient circadian daylighting" based on a limited and simplified selection of parameters relevant ton on-visual effects, while addressing the question of inhabitants' movements within the space, and, thus, brings with it new perspectives on how these new factors could potentially influence building renovation options.

2. Non-visual daylight simulation in row houses

In the case of Boston, Massachusetts, row houses built throughout the 19th century dominate the urban landscape; in 1969, 98% of the 2900 residential buildings in the South End neighbourhood were masonry row houses [42]. Conservation laws prohibit the alteration of townhouse facades, so windows must remain the same shape and style as originally built. Row houses built after the land reclamation projects of the mid-1800s are standardized in style and shape. Today, a significant portion of these originally single-family houses have been converted into apartments, again in a somewhat standardized fashion. These factors make Boston row houses an interesting case study of the interaction of renovation and its effects on natural lighting conditions in the context of human biological needs, especially since most row houses were built before the widespread use of electric lighting i.e., with daylight as the primary light source.

Given what we know about photobiology and row house configuration, it is possible to design a preliminary simulation framework to determine which of a range of common design parameters within the limits available in row house construction might have the most impact on daylight exposure and therefore light–dark cycle patterns.

The applied methodology can be summarized as follows: A yearly illuminance profile was simulated for a variety of possible apartment scenarios with a vertical sensor that moved from the front to the back of the room and rotated, and the percentage of waking hours when the natural light on the sensor was sufficient to meet circadian requirements was calculated using a threshold lux value based on previous research [43]. Seven common variables in row house apartment design were explored, including factors like placement of the room partition, interior paint colour, and window configuration. The timing of light received was examined using temporal maps. Finally, a few "improvement scenarios" on some common but suboptimal apartment configurations were proposed and simulated to see if improved timing and duration of light could be achieved given a moving sensor.