Modeling 'Non-Visual' Effects of Daylighting in a Residential Environment

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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.

Keywords: Daylighting, Circadian, Non-visual effects, Health, Residential, Building Simulation

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 hour) clock with the environment. The circadian pacemaker is an internally generated oscillator with a period that runs close to, but not exactly 24 hours, 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-hour 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-hour light–dark cycle causes desynchrony between the circadian system and external time, leading to insomnia, excessive sleepiness, metabolic disorders and increased risk of cardiovascular disease,

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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-hour world and development of a highly disruptive condition called non-24-hour 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]. Whıle 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 (4100K) 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 day-time 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 [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.

2.1 Biological thresholds

While current lighting design is guided by industrial standards that define the minimum light required to maintain good vision (most commonly expressed as workplane illuminance [lux] i.e. as the amount of light falling on a horizontal surface), no such standards exist yet for the non-visual effects of light. Until such standards are available, we are required to make assumptions, based on experimental laboratory data, about the target light level and spectrum required to maintain adequate non-visual function. Visual lighting standards assume that the three-cone photopic colour vision system is mediating the lighting response and are therefore attuned to a light sensitivity spectrum peaking at 555 nm [$V(\lambda)$], and quantified in photopic lux. The non-visual effects of light are mediated primarily by the photopigment melanopsin, which has a peak sensitivity in the blue visible range, ~480 nm, commonly named $C(\lambda)$. When comparing two light sources, the source with a spectrum that more closely matches the spectral sensitivity of the melanopsin photopigment (i.e., the one which contains more blue light) will have greater ‘circadian efficacy’ [44] and will require less light to achieve the same physiological effects than a source with less blue light. To determine what lux values from respective illuminants would achieve a prescribed “circadian-equivalent” illuminance, known radiometric spectra for daylight and other light sources can be used to back-calculate the absolute power in watts of a given light source, as proposed in Pechacek, Andersen and Lockley in 2008 [43]. These irradiance values are then multiplied by an assumed $C(\lambda)$ curve of melanopsin sensitivity to provide a single number of ‘circadian-equivalent’ lux of a given illuminant.

The minimum acceptable ‘circadian’ illuminance is here set based on the simplifying assumptions made in the [43] paper, that led to a threshold of 190 lux of D65 illuminant (daylight) needed to achieve a 100% subjective alerting effect. This value was derived from a publication by [8] defining a dose-response curve for the alerting effects of a 6.5 hour polychromatic light exposure from a study that also examined the dose-response for melatonin suppression and phase resetting [20]. From the dose-response curve, Cajochen et al. found that exposure to ~300 lux to 4100K polychromatic fluorescent light at night was required to maintain maximal alertness [8], which, using the conversion mentioned above, would correspond to a circadian-equivalent threshold for D65 illuminant of 190 lux (given that daylight has a relatively greater blue component than 4100K fluorescent light) [43].

While this threshold can by no means be relied upon to make realistic predictions or recommendations regarding alerting effects during the day (also because the timing, duration and history of light exposure are not taken into account), it remains useful in the present study to establish a preliminary simulation workflow and identify likely inter-dependencies between design factors that are expected to affect non-visual effects.

To account for the spectral variations observed for daylight depending on weather and time of day, different thresholds were actually applied depending on orientation and sensor (eye) position: 190 lux (D65 illuminant i.e. daylight) was used for south-facing facades when the sensor point was in the front one-third of the room, 180 lux for north-facing facades when the sensor point was in the front one-third of the room (a slightly 'bluer' light because of the absence of 'redder' sunlight, and assumed to be well represented by the D75 illuminant), and 250 lux for south- or north-facing facades when the sensor point was in the back one-half of the room and the room was painted a dark colour. As noted in [43], typical 'neutral' wall paints tend to be slightly blue-deficient and thus induce a spectral selectivity effect due to wall inter-reflections that increases with room depth. To estimate corneal illuminance at the eye, eight vertical sensor planes (one per view direction) were modelled at a fixed eye-level height of 152.4cm (5') for the two locations within the space (cf. Figure 1c).

Until more reliable models are developed, the above-mentioned illuminance thresholds should simply be considered nominal values for daytime analyses to illustrate the methodology taken. A similar basis for building a simulation framework for non-visual effects has been discussed in [45] where the same minimum threshold value was considered together with an upper threshold derived from [11] in an attempt to incorporate day-time results as a benchmark for increased likelihood that a non-visual effect will be observed.

2.2 Design of experimental setup

The objective of the proposed framework is to generate information about the quantity of light received at the eye at different points and orientations in representative residential spaces throughout the year, so that they can be compared to a – for now, static – minimum threshold illuminance at the eye based on current photobiology research. In order to build an archetypal row house model, it was necessary to determine average values for factors that have potentially large impacts on daylight availability, such as standard partition size and location, window size, ceiling heights, and typical urban masking conditions [42].

Photos were taken of a sampling of about 20 houses within the Boston South End district (an example is given in Figure 1a) and were used to calculate average measurements and establish different facade and glazing conditions in the area (Figure 1b). These photos were corrected with a graphics program for perspective issues and then compared against physical measurements taken of the basement windows to calculate floor heights and window sizes. Using Google Earth, overall house dimensions and street widths in the South End neighbourhood were also determined. It was observed that most row houses in the South End face another block of row houses of similar height across a 60' (18.3m) street. On average, those facing a park or other open areas still did not have exposure to a full 90 degrees of sky, but were limited by low masking to 81 degrees of sky. Based on these data, a computer model was generated for a row house that was 12.2 m tall, 6.3 m wide, 11 m deep, with three full stories, a basement, and a fourth floor attic. Upper floors were assumed to have three windows in the front and back facades, and the basement floor two windows (the third being blocked by the entry staircase). All glazing was assumed to be clear glass and - based on observation – to be outfitted with Venetian blinds (Figure 1a).

Within this model structure, different configurations could be defined for testing. The room layout was based on one of two common row house floor plans: a two-room stacked plan, or a three-room stacked plan. It is assumed that the rear room was used as a bedroom and was thus closed off, not admitting light to the rest of the apartment, while the front one or two rooms were used as living space and kitchen. In the case of the two-room stacked apartment, the living space was one large room, 5.5 m deep and 6.3 m wide, with no partitions. In the case of the three-room stacked apartment, the living space had two rooms, each 3.7 m deep by 6.3 m wide, with a 2.3 m x 1.9 m opening (equivalent to double doors) between them. The derivation of these models is shown in Figure 1c.

Figure 1. a) Typical Boston masonry row house (Shawmut Ave, South End district). b) Elevation with dimensions measured for reference in designing sample apartments c) Sample floorplans (left) and simplified versions used for study (right) with 2 considered sensor locations and 8 view directions.

Seven variables were considered because of their significant impact on daylight levels in row houses: floor and window configuration (basement with two windows versus third floor with three), urban masking conditions, orientation, room layout (and in particular the presence or absence of a partition), passive or active blind use, wall paint reflectance, and occupant's location within the room (in particular the distance to the window). The occupant's viewing direction was treated separately. An experiment was then designed using a Hadamard matrix of 32 non-overlapping trials [46-47] to produce enough information to draw conclusions from without requiring a full factorial experiment. This design works by assigning a "high" and a "low" value to each variable that represent its respective far extreme values possible (summarized in Table 1), in order to determine their main (individual) and interaction (in combination) effects.

The experiment of 32 trials with the above seven variables was repeated for eight different orientations; facing toward the window wall, away from the window wall, to the left, to the right, right-toward the window wall, left-toward the window wall, right-away from the window wall, and left-away from the wind wall, in an attempt to mimic the movement of the human head turning as an occupant moves through the space. Light levels were calculated in the vertical plane to imitate light hitting the cornea of the eye and were simulated for two locations (variable 6 in Table 1; the two points are shown in plan in Figure 1c) to model an occupant walking back and forth in the space.

Variable	Parameter	High Value	Low Value
1	Floor/window configuration	Third floor, three windows	Basement floor, two windows
2	Masking	38' row house across a 60' street	19' obstruction 120' away
3	Orientation	South	North
4	Room layout	Two room layout	Three room layout
5	Blind usage	Active usage	Passive usage
6	Location of measurement point	6' away from window	17'6" away from window
7	Paint reflectance	80% reflective	20% reflective

Table 1. Experiment variables and parameters with high and low values

2.3 Daylight Autonomy maps

Daylight Autonomy (DA [%]) [48] – defined as the percentage of occupation time a given illuminance threshold can be achieved by daylighting alone – was chosen as the reference metric for analyzing light penetration and distribution patterns over time and space because it is by definition based on a minimal illuminance threshold and because it can provide a synthetic (single number expressed as a percentage) evaluation of annual, climate-based daylight performance that can account for blind control [49].

First, three sample situations were reviewed in plan: a South-facing apartment on the third floor, a South-facing apartment on the basement floor, and a North-facing apartment on the 3rd floor. A vertical grid with sensors pointing toward the window (shown in Figure 2a for the 3rd floor South-facing apartment) provides valuable preliminary information as the human head (the light "sensor" in this simulation environment) is concerned with light hitting the eye. The location of the eye varies as an individual moves back and forth in a room, but also up and down, as an occupant sits, stands, rotates his or her head, etc. The vertical maps estimate what might hit the cornea at different heights and lateral positions when looking straight ahead and give a somewhat different picture of the Daylight Autonomy falling on a horizontal surface inside these apartments, shown for comparison purposes in Figure 2b for a horizontal sensor grid at a height of 160cm and for a DA threshold of 190 lux. Around sitting to standing height (120-180 cm), Daylight Autonomy as calculated on a vertical grid (its sensors pointing toward the window) is overall higher than that given by a horizontal grid when the 'sensors' are pointing up. All three of these apartments typologies reach vertical Daylight Autonomy values around 70% in the front portion of the room close to the height of the human head when standing or sitting. One can also see that the space directly behind the doorway in the partition exhibits higher vertical Daylight Autonomy values than the remainder of the space, 30-70% as compared to 0%. Note that because the vertical sensor plane is further from the window itself, the contributions from all windows start to add to each other (unlike the very first row of sensors at the window for the horizontal grid where each window has a clear dominant contribution).

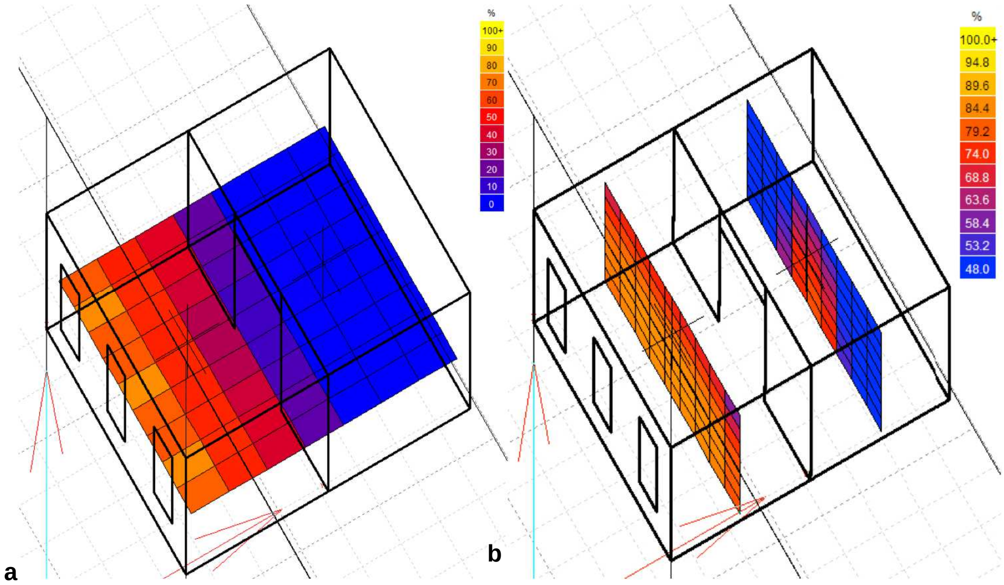

Figure 2. Vertical (a) and Horizontal (b) Daylight Autonomy map for South-facing, 2nd-to-top floor, 0.8 reflectivity walls, divided room, low urban masking.

3. Analysis and results

The DA maps discussed in the previous section provide a framework in which to understand the results of the larger experiment. The daylight autonomy was calculated using Daysim for each of the 32 trials derived from all combinations of variables listed in Table 1, and for each of the eight viewing directions. From this information one can calculate 'overall' average DA values for each view direction (Figure 3). As could be expected, the peak 'average' DA occurs when facing directly toward the window, when all other variables are accounted for. The light level then falls as the viewer rotates his/her gaze about the room, reaching a minimum when facing the back two corners, where some light is lost presumably due to inter-reflections. The left side sees less light than the right side on average because of the asymmetry of the tested situations, which included basement apartments where the leftmost window was blocked by the entrance staircase.

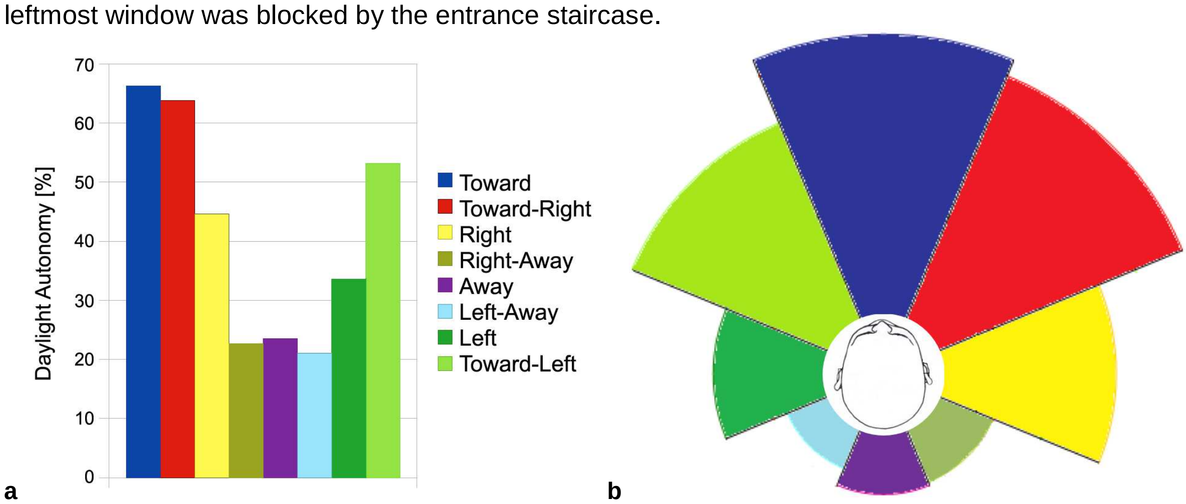

Figure 3. Average daylight autonomies for different viewpoint directions (a) and plotted as a hybrid polar plot (b). In b, data are plotted for 8 equidistant viewing angles with the magnitude of light exposure plotted relative to the front view (dark blue).

3.1 Univariate effects

Using these results, one can calculate the main relative contribution of each variable to determine which design choices have the greatest effect on Daylight Autonomy (Figure 4). The sign of an effect defines whether the variable influences the overall outcome (i.e. DA value) positively or negatively; the actual value of a main effect expresses how much the resulting Daylight Autonomy might differ depending on the value of the considered variable compared to the average of all situations.

Two variables were found to dominate the Daylight Autonomy calculation: distance from the window and wall paint colour. When the user's view includes at least some of a window (toward, toward-right, toward-left, right, and left viewpoints), then distance is the most important factor. When the user faces entirely away from the window (away, away-right, and away-left), however, wall paint colour becomes the most important factor. This makes intuitive sense if the aim is to ensure a minimal illuminance threshold given that direct ocular exposure will maximize daylight, though it neglects glare and overlighting issues, a major aspect that is not treated in the present study but should be incorporated in further development stages of the methodology. Under the same assumptions, when only light reflected from other surfaces can reach the eye, the choice that maximizes the amount and quality/spectrum of light reflected is most important that is, a highly reflective paint colour.

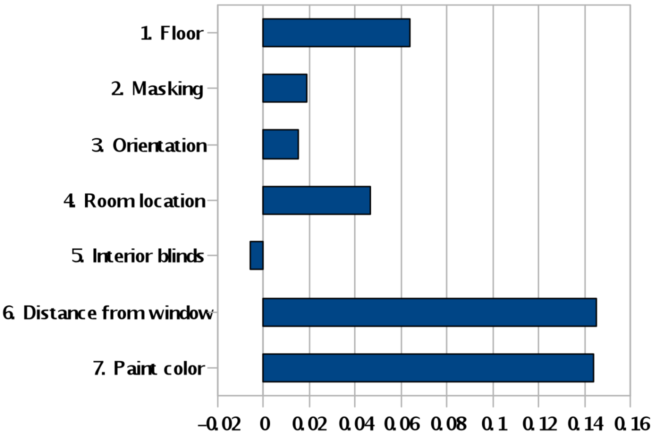

Figure 4. Main effects of variables averaged out over the eight viewpoints

3.2 Variable interactions

Variable interactions were determined by separating the sixteen trials with the highest value of a given variable from the sixteen trials with the lowest value of that same given variable, then calculating the main relative contribution of the other parameters within each group. This allows us to determine whether the influence of the other parameters actually depends on the 'high' versus 'low' value of the considered variable.

For instance, it had been noted that the orientation variable has a very low main effect in all cases, a finding that seemed odd given previous research on the importance of orientation in daylighting performance. By separating the sixteen trials in each viewpoint tested with a northern orientation from the sixteen trials tested with a southern orientation, it was found that all other variables had essentially the same effect in both cases, except as far as blind usage was concerned. In the case of a northern orientation, active blind use had a significant positive effect on Daylight Autonomy, comparable to that of distance from the window and paint colour. In the case of a southern orientation, however, passive blind use had almost an identical positive effect on Daylight Autonomy, essentially hiding the otherwise notable effect of orientation. It would seem that glare control inherent in active blind use on a south-facing facade leads to as much or more daily time with the blinds down as in passive blind use, perhaps due to the greater amount of direct sunlight penetration possible. This effect was found in all viewpoints facing or partially facing the window. Another somewhat counter-intuitive finding was that more masking resulted in slightly positive effect of having taller masking for top floor configurations. Presumably the masking building serves to reflect extra light into the apartment so long as it does not block too much direct sunlight.

The other noted interactions followed intuition more closely. For viewpoints facing toward the window, in the case when less or no direct sunlight is possible (deep location, basement, partition), the choices which maximize light reflected off the interior surfaces of the room, such as highly reflective paint, start to have greater effects. Other notable effects in this viewpoint all relate to masking interactions and similar patterns are found in all the viewpoints facing toward the window. In the viewpoint facing left (toward the side with the blocked window in the basement layout), as could be expected, the floor/window configuration variable has more effect. In viewpoints facing away from the window, there is no blinds-orientation interaction observed. At the measurement point at the front of the apartment, closer to the windows, it is better for Daylight Autonomy values to have a two-room layout, which suggests that the partition reflects more light into the viewer's eye. Conversely, in the single-room

layout, higher Daylight Autonomy results from being at the back measurement point – presumably a consequence of light reflected off the back wall that does not need to travel as far to the viewer's eye. Also highlighting the importance of reflected light in this viewpoint scenario is the observation that tall masking results in higher DA values for the measurement point in the back of the room, suggesting that tall masking can reflect light further into the room.
These findings are summarized in Table 2.

	Floor/window configuration	Masking	Orientation	Presence/ absence of partition	Blind usage	Sensor depth in room	Wall reflectivity
Floor/window configuration							
Masking							
Orientation							
Presence/absence of partition							
Blind usage			Interaction				
Sensor depth in room		Interaction		Interaction			
Wall reflectivity		Interaction		Interaction			
Viewpoint	Interaction	Interaction		Interaction			Interaction

Table 2. Summary table of variable interactions.

3.3 Timing of Light

It is clear that the timing as well as the intensity of light is extremely important to synchronizing human circadian rhythms correctly [3-4,50-51]. As outlined above, light can either phase advance or phase delay the circadian system depending on the timing of exposure. Under normal conditions, light exposure in the later day/early night(~18:00-6:00 h) causes a phase delay of the pacemaker to a later time whereas light exposure in the late night/early day (~6:00-18:00 h) will phase advance the clock to an earlier time. The relationship between the timing of a stimulus and the direction and magnitude of the resultant shift is described in a Phase Response Curve (PRC) and the phase at which light switches from causing a delay to an advance is sometimes termed the ‘crossover point’, and corresponds approximately to core temperature minimum in humans (~6:00 h for someone sleeping from midnight to 8am) Two types of light PRCs have been described across many organisms, including humans; a low amplitude PRC with maximum shifts of several hours (Type 1 or weak resetting) and a high amplitude PRC with maximal shifts of 12 hours (Type 0 or strong resetting) [3]. In practice, most phase shifts experienced by humans are Type 1 shifts as very particular timing of the light is required to achieve Type 0 resetting. The Type 1 PRC provides an essential tool in calculating when to time light, for example in treatment of circadian rhythm sleep disorders, with mistiming of light shifting the clock in the opposite direction to that required, making the sleep disorder worse. Under normal conditions, however, the circadian system requires exposure to a regular 24-hour light-dark cycle to maintain proper synchronization with the external world.

In an architectural space, it is primarily geometry that will affect the timing of daylight. The sun's course traces a unique pattern through the sky as the year passes for any given latitude – in the case of Boston, 42.4 degrees north – and varying weather conditions will add a less predictable dynamic to light input into a building. At any given time of day, the way daylight is distributed across a space will be different from another moment and will depend, for example, on the number and shape of windows, as well as thickness and shape of the external walls, including overhangs. How can this temporal information be best represented? For a single point sensor, a temporal map can be used to give an overall visual picture of a year, based on annual weather files [52] and plotting days of the year along the x-axis and time of day along the y-axis: in Figure 5 for example, two view positions close to the window are compared using the same colour scale (0-1000lux), but one is associated to a view directed slightly rightwards from the window (6a) and the other pointing frankly to the right (i.e. view direction parallel to the window, Figure 5b). This illustrates very clearly how much of an impact the view direction can have on possible exposure to light, and therefore how important studying how a space is actually occupied can be. Such a representation can, for instance, very synthetically show the moments of the year when a given illuminance threshold is achieved (e.g. 190 lux); in the example shown, we see that this is the case for most of the year for these two view directions and at this position. This means that for the considered conditions (which, in this case, were top floor, tall urban mask, south-facing, divided room, passive blinds, close measurement point, 0.2 interior wall reflectivity) and for a viewpoint at least partially facing the window, the ‘circadian potential’ (assessed based on the current assumptions on circadian response and illuminance thresholds) would be high for most of the year at least between mid-morning and mid-afternoon. This type of map can also reveal more subtle differences, like effects of orientation (depending on time of year) or climate, or asymmetries in space layout as a function of the timing of light exposure.

A reason the threshold is so “easy” to achieve in this specific example is probably because the chosen location is very close to abundant daylight and looking consistently at least partly towards the window; an additional reason for that may be that the illuminance threshold assumption was based on a night-time study, but all the subsequent analyses have the same assumption. As noted earlier, however, and accounting for the fact that the proposed approach should be considered as a method or workflow rather than a way to reach reliable design recommendations, it is interesting to see that the visualization of this ‘circadian potential’ over time can offer powerful design support. For example, it might be wise given this temporal information to orient space used in the morning – the bedroom and the kitchen – toward the east (either the right viewpoint in a south-facing house or the left viewpoint in a north-facing house) to take advantage of periods of increased illuminance skewed toward the early hours, a time which will help to overcome sleepiness associated with sleep inertia and help stabilize circadian rhythms.

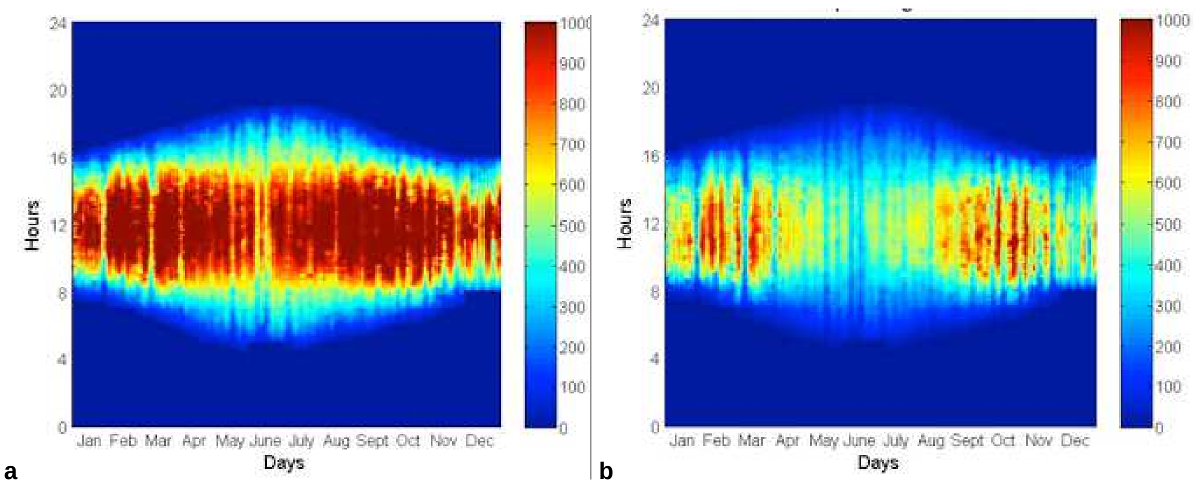

Figure 5. Comparison of timing of lighting as a function of viewpoint (cf. Fig 3): (a) Toward-Right (i.e. towards window slightly to the right) vs. (b) Right (view direction parallel to window). The days of the year are represented on the x-axis and the time of day on the y-axis. Comparison for: top floor, tall urban mask, south-facing, divided room, passive blinds, close measurement point, 0.2 interior wall reflectivity.

A more condensed representation has been proposed by Andersen, Mardaljevic and Lockley [45] in the form of a ‘sombrero’ plot, reproduced in Figure 6, which “categorizes” circadian entrainment in three periods of the day (represented as 3 concentric rings) based on their expected effects on our biological clock, which were discussed in section 2b. It thus offers an even more synthetic visualization of ‘circadian potential’ for a given location, and for four view directions. Its combination with a temporal map information can bring very valuable and intuitive input for design decisions, by quickly pointing out at potential light over- or under-exposure depending on the time of day. For example, high values for late evening exposure (outer ring) should typically be avoided for a healthy dark-light cycles.

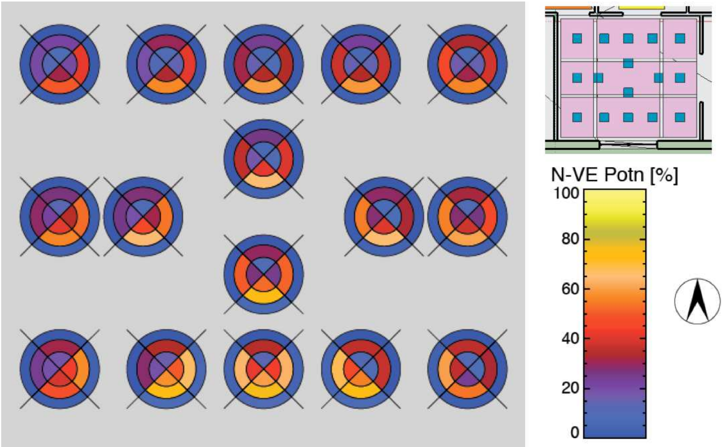

Figure 6. Sombrero plot visualization [45]. Each ring segment gives the cumulated percentage of that time period across the year for which the circadian potential would be achieved for that view direction and at that location.

3.4 Movement and Circadian Lighting

Given that humans will move around the apartment frequently and according to somewhat predictable but highly variable behaviour patterns [53-54], it is necessary to incorporate this variability into our analysis, especially given the strong impact it has on actual light exposure. As a first approximation, we decided to adopt the simplest behavioural model, i.e. random movement. Our model is already highly simplified in terms of occupancy because we restricted the number of considered positions within the apartment to two ('close' or 'far' from window), with eight view directions at each location (i.e. a total of sixteen possible lux values for each moment depending on the combination of location and view), and using a more sophisticated movement model would not make sense. The proposed approach nevertheless serves as a proof of concept as to how the method and generated data could be used to inform design decisions.

We synthesized the data from randomly selected trial scenarios into a single "averaged" number for the year: at each considered moment (every five minutes), one of the sixteen possible results was picked to contribute to the average, as a representation of what a human eye might actually experience through the year as it moves from the front of the room to the back of the room and turns about the room. This differs from the previous information shown, including the average for each trial over all eight view directions shown in Figure 3, because it includes movement from the front to the back of the room for every trial. For all of these cases, including their improvement scenarios, passive blind usage was assumed, given that this behaviour is more typical [49,55-56].

This analysis provided the opportunity to test whether there were different improvement scenarios for different sets of conditions. For instance, if a top floor apartment already has a partition that cannot be removed, tall and high reflective urban masking may be preferable to reflect light into the back of the room, whereas in an apartment without a partition, the urban masking may only serve to block direct sunlight.

Using this method, a "ceiling" of Daylight Autonomy was calculated by determining the Daylight Autonomy for the trial when all variables have their high value (top floor, short mask, south, front room, active blinds, 0.8 reflectivity of walls) *randomized* in terms of view position and direction over the year. The result was 75.8%, indicating that a Daylight Autonomy value higher than this cannot be realistically attained when the user of the space cannot be constrained to look only at the window during all daylight hours.

Next, two cases on the bottom floor, with a divided room and 0.2 reflective walls were tested, as well as two proposed "improvement plans" for each. The first apartment scenario had a short mask and faced south (same conditions as in Figure 5); the second had a tall mask and faced north.

The first combination of variables gave a low randomized daylight autonomy of 26.4%. The second was (as expected) even lower, at 22.8%. This means that for over 75% of the year, occupants of these two common types of apartment setups would be unlikely to be exposed to the required threshold of 190 lux if they randomly move from back to front and turn around.

In terms of improvement schemes, thought was given to what remodels would be most feasible in each setup. Results are summarized in Figure 7. For the first scenario (south-facing, low urban mask), removing the partition (difficult but possible in a typical row house) and painting the walls white (reflectivity 0.8), resulted in a large increase in the randomized Daylight Autonomy, to 58.2% (improvement A). Simply painting the walls white (improvement B) was sufficient to make a noticeable improvement in the randomized Daylight Autonomy, from 26.4% to 41.5%. This is significantly closer to the 50% threshold found in a new IESNA Recommended Practice Standard [57]. For the second case (north-facing, tall urban mask), we examined the situation where the basement ceases to be residential space. In this "remodelled" apartment building, the top floors now are the only occupied ones. After changing the floor/window configuration variable to the "top floor" value, the walls were then painted white – changed from a 0.2 reflectivity to a 0.8 reflectivity (improvement A). These changes had a remarkable positive effect on Daylight Autonomy, raising it to 72.5%, near the limit of what is possible with randomized views. In the second improvement scenario for this situation (B), the orientation of the apartment was flipped without altering the building. This resulted in an improvement in Daylight Autonomy to 47.4%, i.e. not as marked as in the first scenario. Given the generally low illuminance values found for the basement floor even for otherwise favourable situations, and the drastic increase when changing floors, this finding suggests that row house developers should not placing apartments on the basement floor at all from the point of view of 'circadian health' (as derived from the considered model).

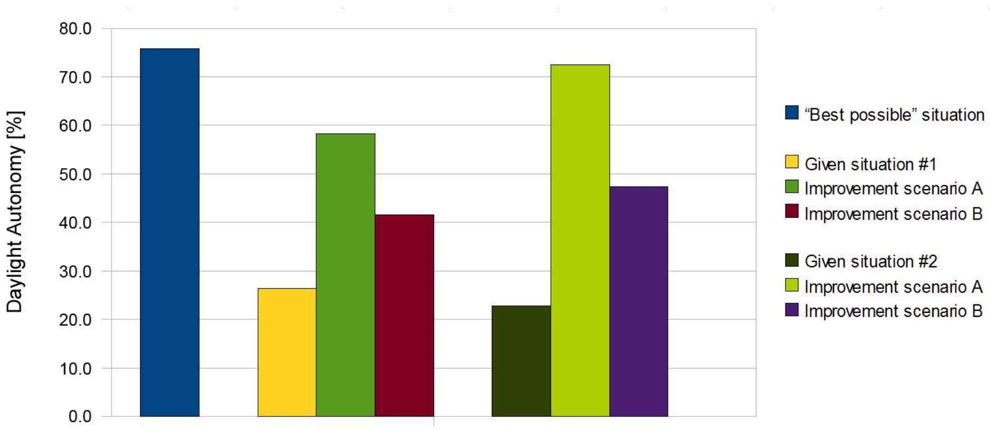

Figure 7. Daylight Autonomy summary table of given situation and of improvement scenarios.

Temporal maps were also generated for the improved scenarios A and B (Figure 8). One can see that all three of these maps display the general overhang-type pattern of decreased periods of high illuminance in the summer, with the highest overall lux values in improvement scenario A (partitions and paint), followed by improvement scenario B (paint only), and the original given case. The spots of most intense illuminance occur in the months of January-February and October-November at about 1:00-1:30 PM solar time. This slight shift of intense light after noon can be attributed to the fact that in the south-facing basement floor configuration, the two extant windows are located in the centre and western thirds of the facade respectively. One may wish to achieve a more beneficial shift of the highest intensity of light toward the morning hours, for the reasons outlined above. This could possibly be achieved by orienting the work areas, such as counters, inside the primary living spaces toward the east. Another solution, if the two windows are placed in the eastern and centre thirds of the façade in the rear of the apartment, would be to re-orient the apartment so the primary living space was in the north-facing room.

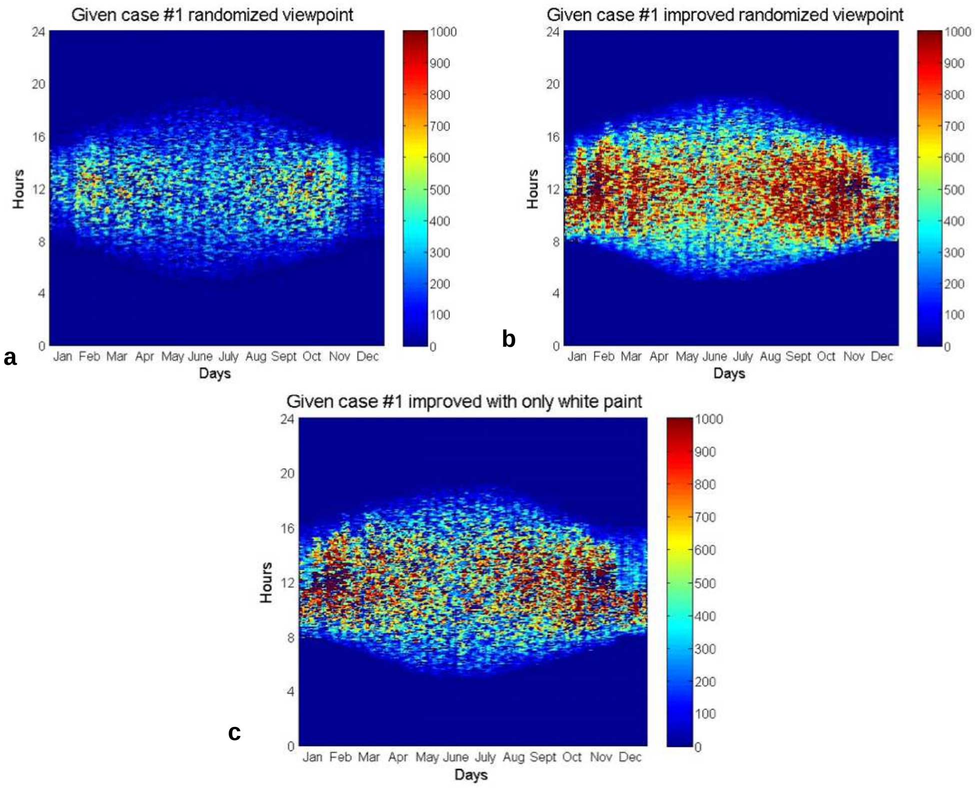

Figure 8. Temporal maps for: (a) given case #1, (b) improvement scenario A, and (c) improvement scenario B

While it is beyond the scope of this paper to address visual comfort issues related to maintaining sufficient light exposure for circadian-related effects, glare is a central concern when discussing daylight penetration options. As a next step in this study, we plan to use glare evaluation – based on annual Daylight Glare Probability calculations [58] as an upper limit; it is the 'useful' circadian potential that should get credit, i.e. only conditions that are not uncomfortable otherwise. The same principle should apply to thermal comfort; if excessive sunlight is allowed inside an apartment or space, overheating may occur, which requires to consider a similar upper limit for "thermal glare" and ensuing cooling requirements.

4. Preliminary design recommendations

Architecture and the eye perform parallel roles in regulating light input to the brain. Just as the pupil fine-tunes the amount of light that enters the eye, the intensity and quality of light reaching internal surfaces are determined by the size and shape of building openings, the light-transmitting qualities of the glazing chosen, and the presence and sizing of shading. Timing is arbitrated by the orientation of the building; for example, a south-eastern facade in the northern hemisphere will receive much more morning light than evening light. The spectral component of light, perhaps the least considered, is first determined by the spectrum of the direct light received from the sun and the sky – morning light, for instance, has a spectral peak of 530 nm, in the yellowish range, while noon light peaks at ~460 nm, in the blue range. Similarly, human behaviour, for example by changes in gaze direction, use of sunglasses, and physical location, also affects the quality of light entering the eye, with overall timing determined by the sleep-wake cycle [2].

The purpose of examining the circadian daylighting potential of historic row houses was to determine the feasibility of coordinating goals of preservation, low energy usage, and biological soundness of a structure that is, after all, first and foremost a dwelling for human beings. As outlined in the beginning of this paper, an apartment with high 'circadian lighting' potential must admit light of the correct intensity, spectrum, duration, and timing. In this section, renovation measures that address the intensity, duration, and timing of light will be discussed within the limited applicability of our simplified model, as well as a brief consideration of the issues of historical accuracy and low energy consumption.

First, these simulations made apparent that the most important – and fortunately, the easiest to change – factor in achieving enough light for a long enough period of time was the presence or absence of highly reflective walls. While the issue of spectral requirements was not researched in this experiment, spectral degradation – more particularly, the loss of blue-shifted light that specifically cues the circadian receptor pigment melanopsin – also could be inferred to be less of a problem in a scenario with highly reflective walls [59]. While it is not new knowledge that white paint leads to a brighter space, it is notable that white paint alone can result in an increase in 'circadian-relevant' Daylight Autonomy of 15%, as found in section 4.4. For a better idea of scale, this means there would be 55 additional days a year, or almost two months, when our circadian light threshold would be met. Note that, while an increase in 'visual' light will obviously happen as well, its magnitude compared to 'non-visual' effects will depend on the spectrum of incoming daylight and on the spectral reflectivity of the walls paint.

The next most powerful single factor in achieving sufficient daylight for circadian purposes was distance from the window. While it is obviously not feasible to only allow occupants to use the 10 feet (3m) of floor area closest to the windows in their apartments, it would be possible to encourage developers to place "service" type areas – closets, bathrooms, pantries, or other areas where occupants spend a relatively short period of time daily – in the "core" of the apartment, and place living spaces where daylight is important – bedrooms, living rooms, and kitchens – in the areas closest to the windows. This statement should come with some reservations, however, as our model does not account for the non-linearity of light duration with circadian response, as noted in sections 2 and 3.2. It has been found, for instance, that the first 15 mins of an exposure is more effective than the last 15 mins: [60] examined the effects of 6.5 h continuous bright white light at night versus 15 mins light every 75 mins. Even though the intermittent exposure represented 20% of the light duration, it induced 75% of the phase resetting response. Therefore subjects may only need to sample 'good' circadian light for a few minutes each hour to get most of the benefit. As long as people can have intermittent access to good circadian lighting, they may get most of the benefit. Human movement and user interaction therefore come into play more to ensure that people spend time within the 'good' places regularly.

Issues of historical preservation add an interesting perspective to this discussion. The possible desirability of painting facades opposite the window façade in white will reflect light deeper into the apartment, but red brick facades are also an integral part of the historic appearance of Boston row houses. Both the re-orienting of apartments toward the more optimal southerly direction (potentially toward the service alley, for example), and the painting of the service alley in a more highly reflective color, also lead to issues of the potentially higher maintenance required in these areas to make these measures effective. The most effective variables like orientation and presence or absence of a partition would also profoundly change the apartment itself whereas government funds are often available for remodelling apartments that have remained true to the original floorplan, but not to those which made drastic changes [61].

At some point preservation of a historic row house and design geared toward maintaining healthy circadian rhythms of the occupant will conflict, particularly in areas such as partition removal and external paint colour. It is to be hoped that both issues will be considered carefully and given balanced precedence.

5. Discussion on the limitations of this research

Due to the simplifications that were necessary during this research, there are certain limitations to applying it to a real-life situation in addition to the ones already mentioned and related to the current state of the art in photobiology research and – as a result – of the preliminary nature of the chosen static illuminance threshold for alertness.

Starting with the actual simulation process itself, there are certain inherent limitations in the software used in the project that make it difficult to model spectral changes in light throughout the space, even though the spectral component of light is an important one in circadian cuing. The DAYSIM software that calculated Daylight Autonomy is only capable of simulating spectrum-neutral spaces; Radiance acts as the core engine for DAYSIM and is a three-channel RGB raytracer, i.e. of limited capabilities to simulate the spectral properties of actual daylight. In this experiment, all spaces simulated were spectrally neutral, which disregards the potential effect of particularly blue-rich or blue-lacking paint could have in reflecting the appropriate wavelengths to the blue-sensitive circadian pigment in the eye.

Other simplifications included modelling the space without furniture. This approximation was made because of the infinite variations possible while placing chairs, counters, tables, and other items, but obviously the placement, shape, and reflectances of these items can make a significant difference to the overall illuminance and spectral distribution of light in the room.

While there are infinite small variations in the row house plan, there are some significant ones that occur with enough frequency to make case studies of these particular situations important to understand the overall nature of light in this type of building. Of particular interest are houses at the end of the block, which often have three or more extra windows per floor on the wall that is not sandwiched between two houses. This adds a significant amount of glazing area to each floor as well as an exposure in a new direction. Also of interest are L-shaped houses, which allow up to three extra windows per floor and decrease somewhat the amount of room area that needs to be lit by these windows. A third common issue that could have a pronounced effect on the natural daylight on an apartment in the installation of window air conditioners, particularly in basement windows. These air conditioners often block half or more of the glazing of a single window, which could affect both the intensity and timing of light received. Another common issue, is the dormer window geometry, often found on the top floor. In this scenario, daylight effectively has to pass through a short "tunnel" before reaching the room; the extra reflections off of the interior of the dormer could potentially result in some light losses.

While the issue of the night-time bedroom was not discussed explicitly here, it has been shown in other papers that the circadian pacemaker as mediated by the human eye is remarkably sensitive to nocturnal light [20]. Based on this information, one can infer the great importance of having a bedroom that is very dark at night for proper circadian rhythm and sleep maintenance [62-63]. This task, given streetlights, car headlights, light from other buildings, and other sources of light pollution during the night, is perhaps even more difficult to achieve architecturally than delivering the correct amounts of light during the day, especially when one adds the caveat that morning light penetration into the bedroom is desirable.

6. Conclusions

This paper examined typical row houses in the South End neighbourhood of Boston with the intent to establish a workflow ultimately aiming to assess a space's "circadian daylighting potential", and what design factors are likely to affect it most. Current research in photobiology was referenced to determine threshold lux values and daily timing likely to result in higher alertness and properly set circadian rhythms for occupants. These threshold values are not to be taken as absolute given the scarcity of evidence and daytime polychromatic light experiments so far, but are interesting for the foundation of a method.

Seven variables were selected that were thought to have a large effect upon the daylight measured inside: floor/window configuration, distance of measurement sensor from the window wall, wall reflectivity, type of blind usage, urban masking conditions, and presence or absence of room partitioning. After determining the greatest variable effects and variable interactions, two given situations were simulated by randomly averaging the data from two different spatial points with eight viewpoints each inside the apartment, and improvement scenarios as well as design recommendations were then proposed together with a discussion of the limitations of the proposed method.

This paper found that large positive changes in Daylight Autonomy can be effected by relatively small changes in an apartment's configuration, such as painting the walls white and/or shifting occupant activities into areas closer to the windows, or avoiding the use of the basement floor as a dwelling. A necessary step to better validate the proposed approach will be to address the question of whether a 'non-visual' analysis truly provides more information than visual quantities: an interesting further analysis would indeed be to question whether design decisions differ when non-visual considerations are brought in compared to simply ensuring higher DA thresholds. On-going work by the authors on a more realistic and dynamic model for simulating the *direct* effects (non phase-shifting) of the non-visual system [64-65] seems to indicate that this might indeed be the case once timing, duration and photic history are better accounted for. As mentioned previously, this type of analysis would ideally also include visual and thermal comfort considerations as upper daylight and/or sunlight penetration limits.

Another area of future work will be to investigate the potential of electric lighting controls to dynamically supplement daylight when needed, as well as the extent to which higher CCT lamps may or may not be needed in residential and/or commercial settings. One possible method to validate such hypotheses will be to measure light at the wrist or – better – at the eye every minute, similarly to the *Daysimeter* device [66]. Such a head-worn device could assess exactly how movement and head orientation affects ocular light exposure and test the validity of predictive models [67].

Despite the embryonic nature of the proposed method given the limited availability of studies on daylight-related non-visual photoreception effects, this paper supports the idea of a lighting simulation framework that will ultimately allow combined and – hopefully – integrated – prediction methods for both visual and non-visual aspects of lighting in built spaces.

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