Circadian Effects of Daylighting in a Residential Environment

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Abstract
This paper examines the effects of housing design upon the amount of natural light available for cuing of the human circadian system. It further assesses whether the conditions present in historic Boston row houses, when considered in the context of human moving around, can be adapted to provide sufficient light to maintain occupants' circadian rhythms. While software has been developed to simulate the amount of light in lux or lumens being received on a sensor point, these programs have generally been used to calculate the light received on a static, horizontal surface, such as a desk or other workspace. For the sake of determining a room's circadian potential, however, the sensor used must be vertical, as is the human eye during the day, and must be able to both rotate and translate – i.e. it must move forward and backward in a room and turn to face different viewpoints, as a human user does. Based on a series of simulations which take into account these factors it is possible to offer suggestions for both restoration and future design.

Keywords: Daylighting, Circadian, Health, Residential buildings, Simulation, Timing of light

1. Introduction

Architecture mediates the boundary between the external environment and the human body, and therefore whether the body is able to fulfill its needs from the environment, such as those for fresh air and light. The human internal clock naturally runs to a different period than the social and solar twenty-four-hour day [1]. This internal clock dictates important physiological conditions, such as hormone production, core body temperature cycles, sleep-wake cycles, and alertness patterns [2]. In order to reset this clock on a daily basis to the external temporal environment, light cues must be received through the eye that are differentiable from those required for vision [3]. Disruption of the circadian system i.e. by insufficient quantity of or inappropriately timed light can cause considerable stress. Previous research suggests that well-maintained circadian rhythms can contribute to faster healing (in hospitals) and increased productivity [4,5]. Daylight is best suited to achieving the spectrum needs of circadian light cues while remaining within comfort levels.

While new methods of architecture following more closely from human biological needs are certainly attractive, merely developing new paradigms for future buildings fails to address issues of historical conservation and reducing energy consumption. Many high-density cities contain historic dwelling places that have been re-purposed as apartment or retail space, and the presence of these structures maintains the traditional character of the area. Furthermore, it is apparent that restricting new construction to the absolutely necessary and reducing the materials used for building is an important step toward energy usage reduction. For both of these reasons, it has become important to consider whether existing structures can be adapted to become more livable residences and working places.

In the case of Boston, Massachusetts, historic row houses built throughout the 19th century dominate the urban landscape; in 1969, 98% of the 2900 residential building in the South End neighborhood were masonry row houses [6]. Stringent conservation laws prohibit the alteration of townhouse facades, so windows must remain the same shape and style as they were built. Row houses built after the land reclamation projects of the mid-1800s are largely 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 modern renovation and its effects on natural lighting conditions. Since most row houses were built before the widespread onset of electric lighting, it is possible that natural daylight was considered more integrally in their design, leading to structures that could better be adapted for biologically and energetically sound living today.

This paper will assess the circadian lighting potential of standard configurations of Boston row house apartments, determine which factors are most important in achieving sufficient circadian daylighting while considering human movement, and offer design suggestions for altering these buildings in effective ways to make them more livable.

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2. Photobiology and Architecture

Light directly alerts the human brain [7] and no other stimulus is as important for entraining circadian rhythms; sleep-wake cycles, activity-inactivity cycles, and social contact cycles each can only effect very minor shifts in circadian rhythms (+/- 20 minutes), while light can cause substantial shifts (+/- 7 hours) [8]. The circadian pacemaker is extremely sensitive to even room levels of light, particularly during the first 6-7 hours of the biological night. The melatonin suppression response, associated with a decrease in sleepiness, saturates at about 200 lux of light from ceiling-mounted cool white fluorescent lamps, while the circadian phase-shifting reponse saturates at about 550 lux [8,9].

The timing of light during the biological day is also very important. Morning wakefulness occurs 1-2 hours after melatonin secretion stops due to light stimulus, whereas the transition into sleepiness occurs 1-3 hours after melatonin secretion starts due to a decrease in light levels [2]. Therefore, light should enter a bedroom about two hours before waking is intended, and light levels should be kept to a low level at least two hours before sleep is intended.

Architecture becomes an important component in this discussion when one realizes that all of these vital components of daylight – intensity, timing, and spectrum – are mediated through the form of surrounding structures. Intensity of light is determined by the size and shape of openings, the light-transmitting qualities of the glazing chosen, the presence and sizing of shading, the size and shape of the space being lit, the global location and position of the overall building, and the depth and orientation of the light receptor, such as the eye or a luxmeter. Timing is arbitrated by the orientation of the building and the shape of the openings; for example, a southeastern facade in the northern hemisphere will receive much more morning light than evening light. The spectral component of light, perhaps the least considered, is determined by both 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 – and the characteristics of the reflected light received, which is determined by the color of the surfaces on which the light bounces and how many times the light bounces (determined by the depth and geometry of the space) [10].

Americans, on average, spend about 90% of their waking hours indoors [11]. Increase in distance from a window, and therefore amount of light and the corresponding subjective and objective alertness, have been linked to a decrease in productivity and higher absenteeism in the workplace [12]. Light clearly has a profound effect upon human health. 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. One can look at the lighting levels throughout the day as a biological criteria for health in the home. This is also a prototype of the kind of study that could be done in other spaces, such as offices, schools, and laboratories.

3. Daylight simulation in row houses

Given this information about photobiology and row house configuration, it is possible to design an experiment to determine the most important design parameters within the limits available in row house construction. Computer simulation tools were used to generate information about the quantity of light at different points and orientations in the space throughout the year, which was compared to a minimum value based on current research, 190 lux, needed for alertness and used to compute a daylight autonomy percentage throughout the year [10].

3.1 Optimization of the experimental design

Floor/window configuration, masking conditions, orientation, presence/absence of a partition, blind usage, distance of the sensor from the window, wall reflectivity, and user viewoint were selected as the most important design parameters. An experiment then had to be designed that would both rely on enough trials to gather sufficient information to make conclusions from and on few enough trials to be feasible. A full factorial experiment, in which all possible combination of variables are tested, becomes virtually impossible to accomplish after reaching a limited number of variables. However, one can derive a great deal of the same information from a much smaller experiment of non-overlapping trials, designed by constructing a Hadamard matrix of 32 tests [13,14]. This design works by assigning a "high" and a "low" value to each variable, denoted by a + or – sign respectively in the matrix. These represent the far extreme values possible for each variable. This type of experiment can also be used to quantitatively compare two similar situations, such as facing toward or away from the window wall, upon circadian daylight autonomy.

3.2 Biological thresholds

This experiment also has to make certain assumptions about the goal level of light to be achieved. If the spectrum of a light source more closely matches that of the circadian receptor pigment's sensitivity, less light is required to generate the same physiological effects. To determine what lux values from respective illuminants would achieve 100% alerting effects, known radiometric spectrum for daylight and other light sources can be used to back-calculate the absolute power in watts of a given light source. These irradiance values are then multiplied by the C(λ) curve of melatonin (circadian photoreceptor) sensitivity [10].

Because of the limited research done previously in this area, certain assumptions are made about this circadian lighting curve. An important simplification is that it is assumed to be equally efficacious at all times (i.e. the sensitivity of melatonin does not change during the day) for all users. While this is known to be somewhat unrealistic, e.g. individuals who spend a great deal of time outdoors have decreased circadian sensitivity to light, which new research has only started to examine. It is also possible that as research continues in this area, new data will be discovered regarding the light and spectral sensitivity of melatonin.

For this study, the cutoff for acceptable circadian illuminance was set at 190 lux, based on a publication by Cajochen et al performed with polychromatic light that determined that a 4100 K color temperature lamp must generate 300 lux at the eye to keep observers at peak alertness [15]. This 190 lux threshold was applied as is for south-facing facades when the sensor point is in the front one-third of the room, and was adjusted to account for typical spectral changes as follows: 180 lux for north-facing facades (bluer light, this more 'circadian effective') when the sensor point was in the front one-third of the room, and 250 lux for south- and north-facing facades when the room was painted a dark color and the sensor point was in the back one-half of the room (to account for the spectral selectivity effect due to wall interreflections. These sensor points (planes) were chosen vertical, as is the human eye during the day [10].

3.3 Digital model design

In order to build an archetypal row house model that could be tested in computer daylight simulation programs, it was necessary to determine average values for factors that have a large impact of daylight, such as standard partition size and location, window size, ceiling heights, and typical masking conditions, relying on Whittlesey's book [6], the Google Earth program and personal documentation. Seven variables were defined as having strong impact on daylight levels in row houses: floor/window configuration, masking, orientation, room layout, passive or active blind use, the measurement point's depth in the room, and paint reflectance. The occupant's viewing direction is treated separately. The experiment of 32 trials with the above seven variables was repeated eight times, with the measurement sensor each time 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 the vertical plane. This is an attempt to mimic the movement of the human head turning as an occupant moves through the space, as the different depths of the sensor (variable 6 in Table 1) mimics 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 with high and low values

3.4 Daylight Autonomy maps

Daylight Autonomy [16] was chosen as the reference metric for analyzing light penetration and distribution patterns over time and space. First, three sample situations were looked at in plan, as for the example shown in Figure 1a. In this case, the daylight autonomy spatial grid covers the floor area, and all sensors point up. The grid is set at a height of 5'3," and the threshold for daylight autonomy is entered into the software as 190 lux, the light threshold for maintaining alertnessmentioned earlier. This type of grid is typically more useful to assess the daylight falling on a horizontal work plane, but it can still give an an idea of what areas are more often well-lit during the year. In these spatial maps, we can see a general pattern of increased daylight autonomy close to the windows, with bright spots located directly behind the glazing. Daylight autonomy quickly drops off toward the back of the room, however, and is essentially zero in the entire back half of the room. Overall daylight autonomy is highest in the south-facing apartment on the second-to-top floor, and lowest in the north-facing apartment. In the south-facing apartment on the basement floor, the area of highest daylight autonomy is concentrated in only one corner of the apartment, which seems to limit the circadian daylighting potential of this scenario.

A vertical grid with sensors pointing toward the window gives an added dimension of important information; the human head (the most typical "sensor" in a real environment) translates back and forth in a room, but also up and down, as an occupant sits, stands, bends over, and so on.These vertical maps give a somewhat different picture of the daylight autonomy inside these apartments. The daylight autonomy as measured by a vertical grid, its sensors pointing toward the window, is overall higher than that given by a horizontal grid, sensors pointing up. All three of these apartments reach a daylight autonomy 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 has a higher daylight autonomy that the remainder of the space, 30-70% as compared to 0%. These maps, as shown in Figure 1b, can give a better framework in which to understand the results of the larger experiment.

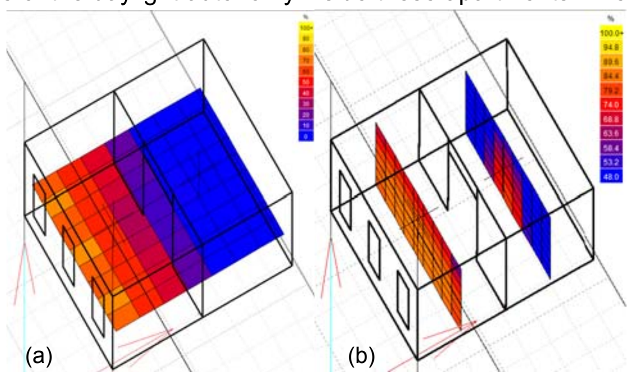

Figure 1. Horizontal (a) and Vertical (b) Daylight Autonomy map for South-facing, 2nd-to-top floor, 0.8 reflectivity walls, divided room, low masking

4. Results analysis

The daylight autonomy was calculated by 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 generate an idea about the average daylight autonomy possible when facing in each direction given the range of different conditions possible, as below in figure 2. As could be expected, the peak daylight autonomy possible occurs when facing directly toward the window. This number then dips as the viewer rotates their gaze about the room, reaching a minimum when facing the back two corners, where some light is presumably lost in interreflections. 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 (i.e. by the entrance staircase.)

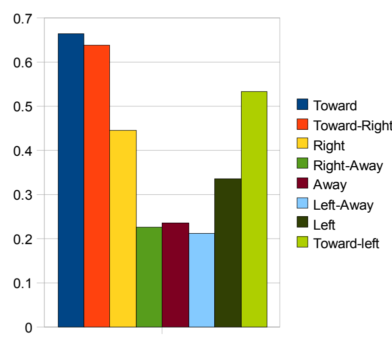

Figure 2. Average Daylight Autonomy for different viewpoint directions

4.1 Main effects

Using these results, one can calculate the main effects of each variable to determine what design choices have the greatest effect on daylight autonomy. Two variables were found to dominate the daylight autonomy calculation: distance from the window and paint color. 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, but when the user faces entirely away from the window (away, away-right, and away-left), paint color becomes the most important factor. This makes sense, since it seems that if direct sunlight can reach the eye (i.e. when facing toward the window), the choice that will most maximize direct sunlight is most important, but when only light reflected off of other surfaces can reach the eye, the choice that maximizes the amount of light reflected (i.e. a highly reflective paint color) is most important. In figure 3, an overall average of the main effects of each variable over the eight viewpoints gives an idea of their relative importance.

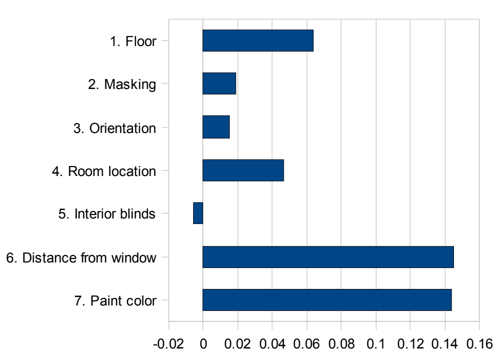

Figure 3. Main effects of variables averaged out over the eight viewpoints

4.2 Variable interactions

Certain unexpected trends can be analyzed and explained as variable interactions. Variables interactions were determined by separating the sixteen trials with the high value of a given variable from the sixteen trials with the low value of a given variable, doing the same main effect calculation for each set of data as above, and then comparing the two effects to find marked differences in the main effect of all other variables. This analysis led to a number of significant interactions, summarized in Table 2, and to a better understanding of some of the results obtained for main variable effects.

	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

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 in this area. 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 for blind use. 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 color. However, in the case of a southern orientation, passive blind use had almost an identical positive effect on daylight autonomy, essentially masking 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.

4.3 Timing of Light

It is very clear that the timing as well as the intensity of light is extremely important to synchronizing human circadian rhythms correctly [1,8]. In order to feel alert and wakeful at the beginning of the day, human beings need light exposure one to two hours before starting mentally or physically intensive work in the morning, since wakefulness seems to occur one to two hours after melatonin suppression occurs due to increased levels of light [2]. In the United States, where most standard jobs begin at eight or nine o'clock, this means that light exposure ideally should begin at six to seven o'clock. In Boston, the latest sunrise of the year is around 7:15, making this type of lighting an attainable goal. In other cities in the US with more northern latitudes, such as Minneapolis, the latest sunrise of the year is around 7:50, meaning that either artificial lighting must be used to achieve this circadian goal or that workplaces should consider later starting times.

Timing of daylight is primarily affected by the geometry of a space. The sun's course traces a unique pattern through the sky as the year passes for any given latitude – in the case of Boston, 42.36 degrees north. At any given time of day a different portion of a room is shaded, depending on the number and shape of windows, as well 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 [17]. On this map, the day of the year is represented on the x-axis and the time of day is represented on the y-axis. The amount of light is represented by a color scale, going from blue (low levels of light) to red (high levels of light). The amount of light at each point in time is represented by a pixel of appropriate color.

The trials pairs compared up to this point have faced the same direction, either both toward the window or both away from the window. An important parameter to take into consideration is also the actual viewpoint, and how it will affect the temporal pattern of light. The effect of viewpoint is illustrated in the series of eight temporal maps shown in Figure 4 (keeping the same 0-1000 lux color scale), which apply to: top floor, tall mask, south-facing, divided room, passive blinds, close measurement point, 0.2 reflectivity.

Since morning light is so important in setting circadian rhythms and in initiating alertness for the day, 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. This could be accomplished putting workspaces on the east wall in the kitchen, for example. In the basement, where only two windows are possible, it's probably preferable to have a bias toward window on the eastern half of the facade.

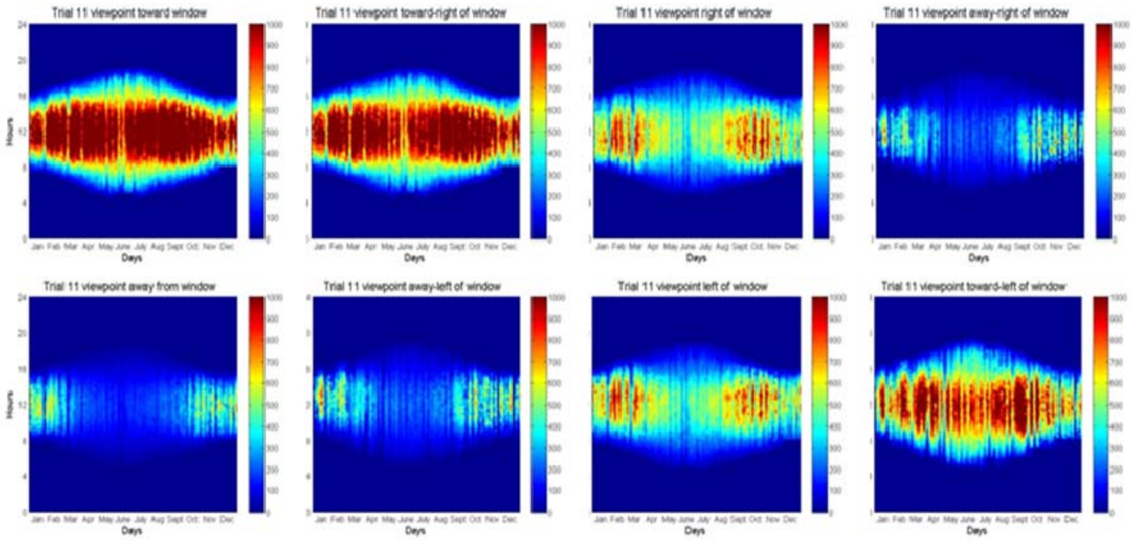

Figure 4. Comparison of timing of lighting as a function of viewpoint for: top floor, tall mask, south-facing, divided room, passive blinds, close measurement point, 0.2 reflectivity.

4.4 Movement and Circadian Lighting

Given that a human being in the apartment will move around frequently and unpredictably, it is necessary to investigate to what extent any design or retrofit decisions attempting to increase the circadian potential of the space will be effective. This question was undertaken by synthesizing the data from selected trial scenarios into a single "averaged" number for the year that takes into account random movement. The simplification was made that this random movement could be represented by selecting one of two locations in the room – the close (6') or far (17'6") value used in the experiment – and one of eight viewpoints at each location for each point during the year, then using this new series of lux values 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 viewpoints, because it includes movement from the front to the back of the room for every trial.

This also provided the opportunity to see if there were different ideal improvements for different given situations. For instance, if a top floor apartment already has a partition that cannot be removed, tall, high reflective masking may be preferable to reflect light into the back of the room, while for an apartment without a partition, the masking may only serve to block direct sunlight.

A random number was generated from 1 to 16 for every temporal point during the year calculated by the Daysim application – i.e. every 5 minutes. This number was then used to select an illuminance value for that point in time from one of the lists of periodic lux values generated by Daysim for each room location and viewpoint. Using this method, a "ceiling" of daylight autonomy was calculated by determining the randomized daylight autonomy of the trial when all variables have their high value (top floor, short mask, south, front room, active blinds, 0.8 reflectivity of walls). The result was 75.8%, indicating that a daylight autonomy higher than this probably cannot be realistically attained when one considers that the user of the space cannot be constrained to look only at the window during all daylight hours. For all of these cases, including their improvement scenarios, passive blinds were assumed, given that this behavior is more typical [10].

Next, two given cases with some undesirable variables were calculated, as well as two proposed "improvement plans" for each based what a designer, developer, or apartment owner could reasonably change in this apartment setup. The first case considered a theoretical apartment with the same geometry as the conditions illustrated in Figure 4, i.e. bottom floor, short mask, south-facing, divided room, passive blinds, 0.2 reflective walls. This combination of undesirable variables gave a fairly low randomized daylight autonomy, 26.4%, with temporal variations in illuminance given in Figure 5a. Removing the partition and painting the walls white resulted in a large increase in the randomized daylight autonomy, to 58.2% (Figure 5b). But even the relatively trivial decision just to paint the walls white (Figure 5c) will make a noticeable improvement in the randomized daylight autonomy, which would rise to 41.5%. The second case assumed the following variable values: bottom floor, tall mask, north, one room, passive blinds, 0.2 reflectivity and gave an unpleasantly low daylight autonomy of 22.8% and investigated the effect of converting the basement to storage or laundry i.e. occupying only top floors (with corresponding window configuration). If the walls were then painted white – changed from a 0.2 reflectivity to a 0.8 reflectivity -, a remarkable positive effect on the daylight autonomy was observed, raising it to 72.5%. If the orientation of the apartment was flipped without altering the building, a significant improvement in daylight autonomy of 47.4% was also observed, although not as marked as when changing paint.

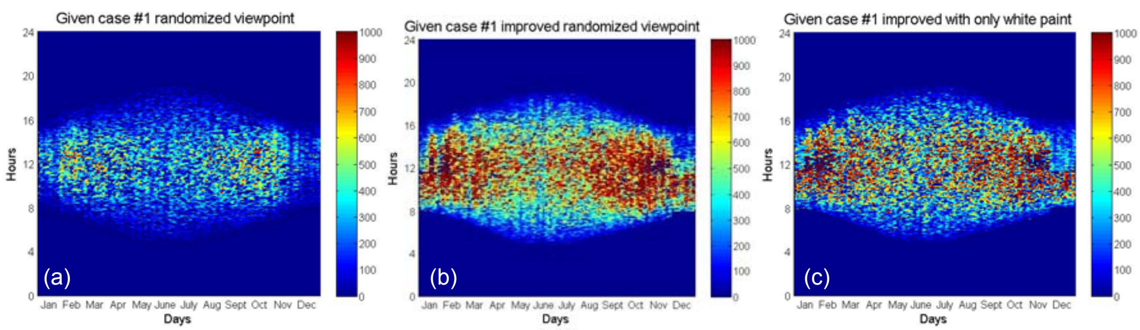

Figure 5. Temporal maps for given case (a), white walls and no partition (b), and paint change only (c).

5. Preliminary design recommendations

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. 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 daylight autonomy of 15.1%, as found in section 4.4. For a better idea of scale, this means there would be 55 more days a year, or almost two months, when circadian needs would be met.

The next most powerful single factor in achieving sufficient daylight for circadian cuing was distance from the window. While it is obviously not feasible to only allow occupants to use the 10 feet 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.

The drastic improvements observed when going from basement apartment to top floor apartment accounting for the randomized viewpoint suggests that it is unwise to place apartments in the basement at all. Perhaps this space could be used for services, such as laundry facilities or storage. It is also apparent that removing partitions in the living space creates an apartment that is more evenly and more fully lit. This, however, can become a historical preservation issue, since often government funds are available for remodeling apartments that have remained true to the original floorplan, but not to those which made drastic changes [18]. Based on the findings of these experiments, it is also recommended to orient living spaces used frequently in the morning – i.e. the kitchen and bedroom – so that occupant viewpoints are most often toward the east. Placing the workspaces, such as counters and sink, on the eastern wall may result in brighter light being received in the morning, a time when circadian rhythms relating to alertness and metabolism are relatively easy to set for the entire day. If this scheme is followed, glare control becomes very important. If possible, living spaces should be oriented south, regardless of primary street orientation. Even if the house at large faces north, what is decided to be the “dominant” living space should probably be placed in the southern half of the building, such that users can receive direct sunlight as well as reflected sunlight through the glazing.

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 color. It is the hope of this paper that both issues will be considered carefully and given equal precedence.

6. Conclusions

This paper examined typical row houses in the South End neighborhood of Boston with the intent to assess their circadian daylighting potential and what design factors most affect their circadian daylighting potential. Current research in photobiology was referenced to determine what minimum threshold lux values and what daily timing resulted in highest 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.

This paper found that large positive changes in daylight autonomy can be effected by relatively small changes in the apartment configuration, such as painting the walls white and/or shifting occupant activities into areas closer to the windows. It is possible that in order to encourage healthy circadian rhythms as regulated by daylight in row house apartment occupants, some widespread changes may have to be made, such as discouraging use of the basement floor as a dwelling. Despite potential challenges, it is very encouraging to find support for the idea that historic row houses can become living spaces not only of remarkable character but also high potential for circadian daylight autonomy, hopefully resulting in healthier and more productive occupants.

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