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COMBINING ANNUAL DAYLIGHT SIMULATION WITH PHOTOBIOLOGY DATA TO ASSESS THE RELATIVE CIRCADIAN EFFICACY OF INTERIOR SPACES

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ABSTRACT

Recent studies have attempted to link environmental cues, such as lighting, with human performance and health, and initial findings seem to indicate a positive correlation between the two. The technical question this paper addresses is the use of Daylight Autonomy (DA) to simulate the probabilistic and temporal potential of daylight for human health needs. It will isolate one topic: human circadian rhythm organization as a proxy for human health. We use outcomes of photobiology research to define threshold values for lighting, which will be used as goals in simulations. These goals will consist of spectrum, intensity, and timing of light at the human eye. The variability of key architectural decisions in hospital room design--orientation, window size, and glazing material—are studied for their impact on achieving the goals. We chose healthcare settings as our case study, with the intent to validate and pursue this research in the future using patient outcomes and data collected in hospitals.

INTRODUCTION

In the past century, hospital design, like architecture in general, has seen the marginalization of functional daylighting paralleling the emergence of more complicated building requirements and new technologies. In response, theoreticians such as Christopher Alexander sought to reintroduce environmental connection, especially daylighting, arguing its benefit to human health [1]. This can also be seen in the evidence-based design movement, which seeks to apply research to building design to improve medical outcomes [2] [3]. In today's healthcare design community, the role of daylight and facade design in patient health is widely discussed [4]. And circadian-sensitive design is gaining prominence through the Green Guides for Healthcare Design [5].

Light affects humans on physical [6], physiological [see refs in 7], and psychological levels [8], though the results are not always conclusive [9]. As the relationship is complex, some level of simplification is necessary in order to make an objective assessment. We chose to pursue the human health-light connection from a physiological perspective. Research into photobiology, especially circadian photoreception, has advanced to a point where specific lighting implications can be proposed. Previous research has reported dramatic healthcare outcomes in daylit environments [10] [11] [12] although the mechanism and photoreceptor systems mediating these effects are as yet unknown. We aimed to advance this research beyond windows, to describing the characteristics of daylight that may promote human health by providing lighting for the appropriate synchronization of circadian rhythms, and then make specific daylighting recommendations, grounded in biological findings.

Many aspects of human physiology and behavior are dominated by 24-h rhythms that have a major impact on our health and well-being. For example, sleep-wake cycles, alertness and performance patterns, core body temperature rhythms and the production of the hormones melatonin and cortisol are all regulated by an endogenous near-24-hour oscillator in the suprachiasmatic nuclei (SCN) of the hypothalamus. The cells in these nuclei spontaneously generate rhythms with a period close to, but not exactly 24 hours, and are therefore synchronized to environmental time by the 24-hour light-dark cycle. Light information is captured exclusively by the eyes using specialized retinal photoreceptors and transduced directly to the SCN via a dedicated neural pathway, the retinohypothalamic tract (RHT). Each day the light-dark cycle resets the internal clock which in turn synchronizes the physiology and behavior controlled by the clock. Recently a novel opsin, melanopsin, was discovered in the mammalian eye, including humans [13], which has been shown to be the primary photopigment of the RHT. Melanopsin is short-wavelength sensitive (λ_{max}~480 nm) and animal and human studies have demonstrated short-wavelength sensitivity for a range of circadian, neuroendocrine and neurobehavioral responses to light [14][15].

In humans, ocular light exposure induces a range of 'non-visual' responses via the RHT including resetting the circadian clock, suppression of pineal melatonin, cortisol elevation in the morning, and an acute alerting effect on the brain. At night, white light improves subjective and objective markers of alertness in a dose-dependent manner [16], similar to that of melatonin suppression and circadian resetting [17]. These responses saturate at ~200-500 lux vertical illuminance with a 4100K fluorescent source following 5 h of dim background exposure (10 lux). While dose-response curves for different wavelengths of light are not yet available, the effects have been shown to be most sensitive to short-wavelength light as predicted for a melanopsin-driven photobiological response [18][19]. White light will also improve alertness in the day-time [20][21]. The mechanism for how light improves alertness is not yet known. Melatonin suppression by light at night is accompanied by a simultaneous decrease in sleepiness and, given melatonin's close relationship to the timing of sleep in diurnal mammals, suppression of melatonin has been postulated as a potential route by which light improves alertness. This mechanism cannot account for improvement in day-time alertness by light, however, as no melatonin is produced at this time. It is possible that direct alerting responses to light involve different processes during the day and night [19].

In addition to spectrum and intensity, light timing, duration, pattern and prior exposure history are critical aspects for determining how light stimulates circadian and other 'non-visual' responses [7] [22]. We have focused on spectrum in the current paper as recent advances have been made in defining the spectral sensitivity of these functions [14] and altering light spectrum may be a relatively simple way to improve light-dependent circadian organization. The precise definition of the human circadian action spectrum (C(λ) is still underway and therefore, while we will focus on a particular definition of (C(λ) in the current analyses, the findings of this paper are not specifically dependent on the curve presented, or any curve, and thus a consensus curve may be substituted into the process described here as knowledge advances. The approach is relative, applicable when comparing design options to one another, but should not yet be taken as an absolute measure of the circadian efficacy or health potential of a space.

SIMULATION PARAMETERS

Simulating the light-dependent stimulation of the circadian photoreception system (which we have termed 'circadian efficacy') of a space is problematic for many reasons. In addition to highlighting these problems, this paper will suggest a simulation method, from which reasonable assertions regarding the circadian efficacy of a space may be made.

Since the circadian efficacy of a light source is partly based on illumination intensity, it is critical to the process that follows to establish a reasonable daylight illumination goal. Daylight Autonomy takes into account daylight's variability due to time, season, and weather, all of which makes the prediction of illuminance at a specific point somewhat uncertain. Daylight Autonomy may be calculated using the RADIANCE-based DAYSIM simulation program, both of which have been extensively and successfully validated for daylighting calculations [23].

This paper uses Zeitzer et al (2000) and Cajochen et al. (2000) to benchmark the sufficiency of the circadian and alerting potential of daylight, respectively. In this study, exposure to ~300 lux for 6.5 h using a 4100K lamp (Philips) achieved maximum subjective alerting during the night [16][17]. To use 300 lux (vertical) as the daylighting illuminance goal, however, would not account for key spectral differences between these two sources.

Traditional illuminance measures, such as footcandles or lux, are calibrated to the eye's light sensitivity, V(λ), to describe apparent brightness. Since melanopsin has a different spectral sensitivity, a different measure is necessary to describe circadian efficacy [18]. Given these parameters, it is essential to understand the radiometric properties of source spectra studied. So, a system of equivalencies is proposed and detailed in Pechacek et al., [24]. To summarize, an inferred radiometric spectrum of a known light source is multiplied by the C(λ) curve to determine a circadian weighting [W-C(λ)]. The application of this calculation method to a range of common illuminants is given in Figure 1.

With these factors in mind, the 4100K lamp used by Cajochen, et al. (2000), at 300lux (vertical) has an approximate circadian power of 0.27 W-C(λ) (see Figure 1 where circadian power was normalized to 1 lumen).

For daylight, one further complication appears in that daylight changes in apparent color temperature depending on time of day, orientation, and weather conditions. The north sky on a clear day, for example is significantly bluer than morning sunrise. To account for this variability, D65 [25] is assumed for south, east and west orientations (it will over-report blue contribution during direct exposure (compared to D55 [25]) but underreport it during indirect exposures), and D75 [25] for north orientations, When transmitted through a double-pane, clear, low-E window [26], the same circadian power of 0.27 W-C(λ) will then be achieved with only 190 ± 20 lux of daylight, depending on orientation and time of day.

The reason why daylight is significantly more circadian-efficient than the 4100K lamp is that daylight is naturally blue-shifted (its spectral peak of 480nm (for D65) corresponds with the estimated peak sensitivity for circadian photoreception [14]) whereas the 4100K lamp has distinct peaks in the green and red portions of the spectrum.

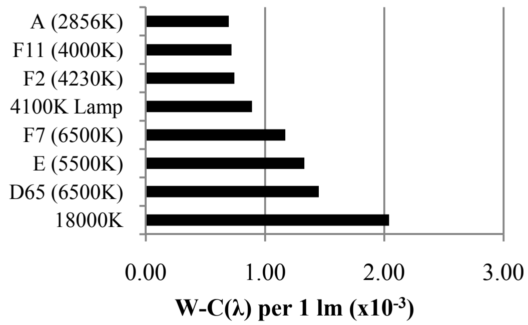


Figure 1: Circadian-Weighting of Illuminants

In addition to spectrum and illuminance, the photobiology literature also places emphasis on timing, duration, and contrast—here simplified as "timing." In a hospital room, the patient is assumed to be largely stationary. This allows for the evaluation of daylight in one location. For the purposes of calculating DA, a 12-h day (06:00-18:00) is assumed as this is the average daylit period.

The temporal mapping that follows is used for a more detailed analysis of lighting conditions over time. These diagrams, derived from DAYSIM output files, display the shifting peak illuminance of daylight, accounting for weather, season, and orientation. The test cases presented will have obvious daylight timing effects—east-facing rooms will experience bright light in the morning, while those facing west will experience it in the evening.

ECOTECT is used as the modeling interface from which the DAYSIM program is launched. The subsequent output was then modified in DAYSIM to match recommended simulation parameters and material properties [27]. A MATLAB-based script was used to translate DA output data into temporal maps which show the timing and intensity of daylight with respect to a fixed position [28].

This simulation process is illustrated in Figure 2. The feedback action allows for refinement of the design. This process builds upon a previously published two-way approach to daylighting simulation. Contextual information, in this case, refers to the site characteristics such as orientation and weather. Design definition includes the subject space's physical properties [29]. Furthermore, daylighting is not the only demand placed on a proposed design. The optimizer included in Figure 2 is thus recommended to refine the subject space's properties accounting for other criteria such as comfort and energy efficiency.

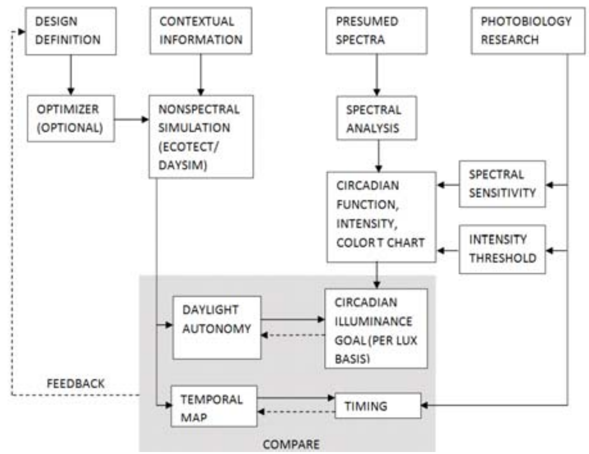
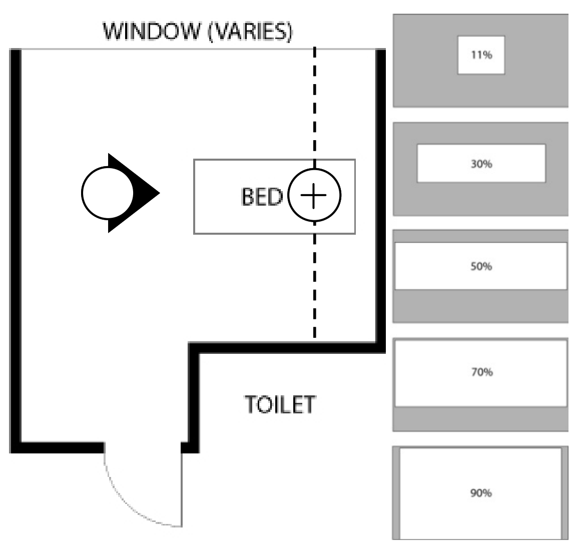


Figure 2. Overview of the process linking space lighting considerations to threshold illuminance values and medical data from photobiology research.

APPLICATION TO A PATIENT ROOM

This paper focuses on a patient room located in Boston, USA. The room dimensions were established based on information published by the AIA and the US Department of Defense [30]. A Hill-rom Versa Care bed system measures 1.02 m wide, 2.4 m deep, and 0.94 m high; its location is shown on Figure 3 below. To best account for clearances and accessibility requirements, a room 4.88 m wide and 3.96 m deep is used in this study. Each patient room is required to have an adjacent toilet/shower room [30]. In this study, the toilet room is placed on the corridor-side of the patient room rather than on the facade for daylighting purposes. The target point chosen for analysis is as shown on Figure 3, is 1.22 m above the finished floor.



FigureFigure 3. L: Hospital patient room configuration. Test point is noted by "+" and vertical illuminance test plane by a black dashed line as viewed from the elevation marker at the foot of the bed. R: test window configurations by glazing factor (%).

The room was assumed to be oriented due north, south, east, or west to demonstrate how changes in orientation affect daylight illumination levels. Glazing fractions of 11%, 30%, 50%, 70%, and 90% were also chosen to demonstrate how changes in window size further affect interior illumination levels [31] (Fig. 3). Spectral data for glazing material was obtained from Lawrence Berkeley National Laboratory's Optic 5 program [26] and Pilkington 6 mm glass was chosen for this experiment. Windows were assumed to be double pane with a clear, Low-E outboard pane.

Daylight Autonomy Results

This DA evaluation tests how effectively natural light reaches an imaginary patient in a hospital bed. In this case, DA is used spatially and temporally with respect to illumination and design options. DA, expressed as a percent (%) at a target point (i.e. the patient's head location), gives a probabilistic rating of achieving the circadian illumination goal and can be used to compare design options (Fig. 4). The circadian efficacy of daylight can be calculated using an equivalence chart, so that the target illuminance is weighted for spectral composition. DA as expressed in a plane shows the spatial dimension within one design variation. Temporal mapping of illuminance at one point gives time and illuminance information, but does not provide spatial data. The confluence of these three approaches provides an objective assessment of the circadian potential of the space through simulation.

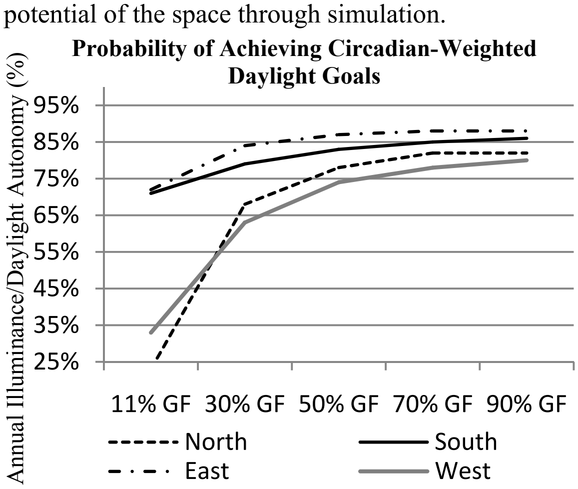


Figure 4: DA (%) at Test Point (190 lux or 180 lux (north), 06:00-18:00h) by Glazing Fraction (%) for North, South, East, and West Facing Hospital Rooms in Boston, USA.

Figure 4 documents how varying room orientation and glazing fraction affects its circadian potential compared to the spectrally-weighted illumination goal. In each case, the room was merely rotated to the test orientation, not mirrored, so differences in the east and west orientations are exaggerated by the effects of cutoff angles created by the window and room geometry. North and west façades at 11% glazing fraction achieve the circadian-weighted daylight illumination goal less than 35% of the time in Boston. Additionally, these results suggest a point of diminishing return at around 50% glazing fraction for all orientations. While these results are compelling, they represent only a partial analysis because they do not consider the temporal or spatial distribution of daylight.

The realization of target DA spatially is described in Figure 5. These diagrams display DA at 190 lux (180 lux North) in a vertical plane located approximately at the target location (Fig. 3), perpendicular to the window. A vertical illuminance test plane is used to represent the natural forward looking gaze of a hospital patient. The window is located to the left in each diagram. Circadian-effectiveness varies by as much as 20% or more based on location in the same room. This information can be used by a designer to modify patient position and/or window configuration to make the best use of the daylight available. For example, in the north-facing room, the DA diminishes quickly with distance from the window. In contrast, the east facing window displays strong penetration of daylight into the general location of the patient bed as demonstrated by the diagonal orange-yellow streak from the left (window) to the center of the diagram.

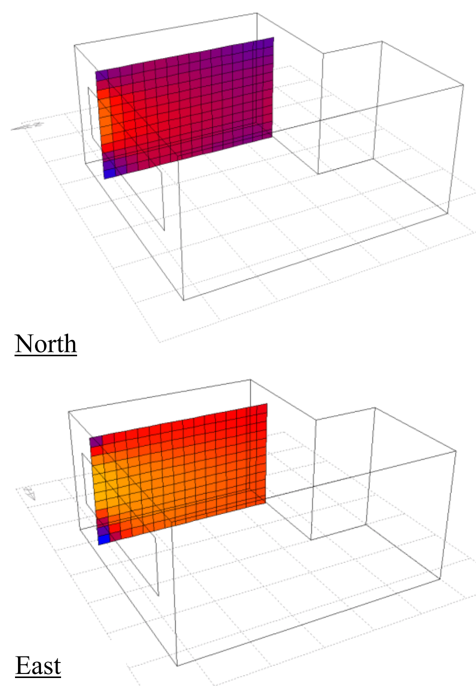


Figure 5: DA in a Vertical Plane at the Patient's Head ("+"), see Figure 3 above, GF=30%, Max Illumin (100%) = 190 lux E, 180 lux N, (0600-1800h). Yellow/Light = 100%, Blue/Dark = 50%. Location: Boston, USA.

Figure 6 demonstrates brightness of daylight at the patient's eye in 5 minute increments over a typical year in Boston. This diagram was derived from output created by DAYSIM (DLL file) [28]. The result indicates the range of times when sunlight will be brightest in the subject space. As timing is a critical factor in effective circadian design, diagrams such as these provide helpful validation of daylight exposure timing. From the data presented in Figure 6, it is clear that an east-facing room performs best in providing intense light in the morning. In contrast, the west-facing window provides intense illumination in the evening. These results may seem obvious for a room with simple geometry and orientation, but more complex spaces with multiple exposures may benefit from this type of analysis.

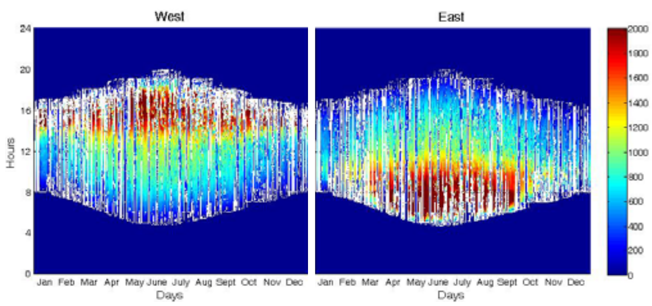


Figure 6: Temporal Maps of West (L) and East (R) Facing Patient Room, GF=90%, Max Illumin = 2000 lux, Min Illumin. = 0 lux. No Shading Device or Blinds Specified. Vertical axis: time (0 h, bottom to 24 h, top). Horizontal axis: day/month of year (Jan, L. to Dec, R.). Location: Boston, USA.

Spectral Neutrality

One of the central assumptions of this paper is the spectral neutrality of the space considered. Built spaces are rarely spectrally neutral, however. A simple experiment was therefore executed, hypothesizing that the spectrum of light received at the eye the weighted sum of the direct sky component's spectrum (which would be a function of $S(\lambda)\tau(\lambda)$)[1] and the internally reflected component's spectrum (which would be a function of $S(\lambda)\tau(\lambda)\rho_{fw}\rho_{cw}(\lambda)$. The purpose of this experiment was to validate the assumption of spectral neutrality, and also to explore conditions in a non-spectrally neutral space using DAYSIM and RADIANCE.

Similar to Wandachowicz (2006), the spectrum studied is divided into three components ($\Delta\lambda$=5nm): Blue 380-495nm, Green 500-625nm, and Red 630-780nm. The source spectrum $S(\lambda)$ [25] and transmission spectrum $\tau(\lambda)$ [26], were summed over their respective ranges and normalized. Simple RGB values were interpolated based on Wandachowicz (2006) to estimate the reflectance spectra $\rho(\lambda)$ of painted walls [32]. The RAL 9003 paint color, in this case, is an approximation of an essentially neutral source.

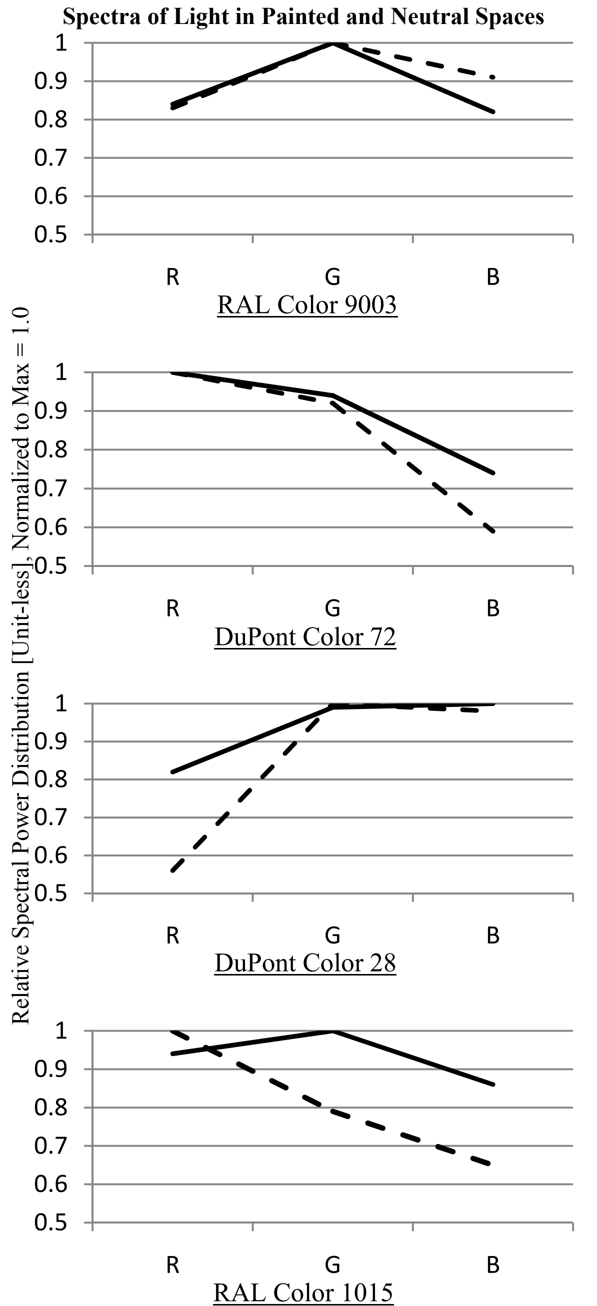


Figure 7: Radiometric RGB for Hypothetical (Dashed) and Simulated Spectra (Solid), Normalized to 1.0, D75 Sky

One key difference in the present paper is the use of radiometric, not photometric, spectra. The radiometric spectra is inferred from source data, then simplified to relative RGB values and normalized at 1.0 max. Used in this manner, RADIANCE is a 3-channel ray tracer which predicts the relative decay in the component

[1] No external obstructions were considered for simplification reasons.

channels following reflections. It is this relative decay which is precisely of interest in this experiment.

For the purposes of this experiment, a south facing room with 30% glazing fraction was simulated in DAYSIM. Two separate simulations were executed in DAYSIM for the patient room example described above. The first followed the parameters described above. From the resulting ILL file, the average illuminance (direct and internally reflected) at the test point was calculated to be 571 lux for the RAL 9003. A second simulation was then used to calculate only the illuminance at the test point due to the direct sky component. For this simulation, the ambient bounces were set to one (1). The average direct illumination was found to be 137 lux. Subtracting the direct from total illumination, the inter-reflected illumination contribution was found to be 76% (IRC=0.76), while the direct was 24% (DC=0.24). Next, a RADIANCE simulation was run for (D75) executed under a CIE overcast sky (R=0.80, G=1.0, B=1.04).

The results of the RADIANCE experiment demonstrate that for spectrally neutral spaces, the spectrum of the light source $S(\lambda)\tau(\lambda)$ is not materially altered (Fig. 7, Top). The hypothetical spectra generally followed the simulated spectra, though with errors as high as 30%. This error rate, however, is within that reported by Wandochowicz when using RADIANCE as a 3-channel ray tracer [32]. These results tend to be specific for overcast conditions, despite the fact that the average total illuminance was used as the DC and IRC benchmark. This is because the effect of direct sunrays at the test location will likely diminish the contribution of interior reflections below the average weighting established from the ILL file above.

On the other hand, walls painted in blue-deficient colors may result in degradation of circadian efficacy. For example, the DuPont 72 and RAL 1015 each caused a reduction in the source's blue spectral component of 14-19%, respectively (Fig. 7). Distance from the source (window) matters—a location closer to the window would have less degradation than one further. These results confirm the findings of Wandachowicz (2006) that interior paint colors diminish the circadian efficacy of a light source through spectral distortions [32].

LIMITATIONS OF EXISTING TOOLS

Simulating both the spectrum and intensity of light is beyond the capabilities of all but the most advanced computer modeling software. Successful simulation of light effects on circadian and other non-visual responses requires an understanding of both, however.
RADIANCE is used as a 3-channel ray tracer in this paper, however, this approach is not without limitations. This is used to simulate and compare relative radiometric spectra. This does not allow for the direct addition of results from separate simulation results as used in Wandochowicz (2006) [32]. Ward and Eydelberg-Vileshin (2002) draw attention to the fact that the number of channels necessary to simulate a continuous spectrum is not clear [33]. Wandachowicz used three separate simulations (3 simulations X 3 channels) to mimic a 9-channel ray tracer. This proved to have a lower error than using RADIANCE as a 3-channel ray-tracer alone, when error was figured based on differences in illuminance results [32]. The research presented here, however, only uses the resultant RGB values to determine spectral shift caused by inter-reflections, not for predicting illuminance values.

DAYSIM assumes an even spectrum, and cannot be used to simulate the sun's ever-changing apparent color temperature. The calculation of DA requires an illuminance goal, and so we here used our best judgement in choosing a value whose circadian-illuminance weighting would most adequately reflect the conditions of various orientations. For instance, north façades will receive bluer light, and so our choice for a D75-based illuminance target. Daylight autonomy calculation also requires specification of a constant daily daylit period without regard for variations in sunrise and sunset times. The choice of a 12 h day is thus a compromise in this regard.

DISCUSSION

Used in the manner described above, or perhaps integrated into current or future software, computer-based simulations allow for the analysis of key health-specific metrics in (day)lighting design.

The simulation method above demonstrates that the choice of glazing type, orientation, size, and position have sometimes dramatic effects on the circadian potential of a design. These values are quite specific to the geographic location and climate, and could also include other externalities such as urban masking. Figure 5 above indicates a diminishing return for most orientations of the subject room (in Boston) beyond a 50% glazing fraction. In hospital design, however, the anticipated beneficial effect on patient outcomes and associated financial impact of higher turnover or reduced bed count may dictate meeting optimal circadian requirements a higher percentage of the time, perhaps informing a choice of 70% or 90% glazing fraction. In this case, the DA provides a key metric upon which to make this important decision.

Additionally, these DA results can be used to inform decisions regarding room configuration. Figure 6 above shows a marked variation between north, south, east, and west exposures for the same patient room.

Because this room's layout was not altered to optimize the patient's access to daylight, the consequences of orientation are exaggerated in the results. Therefore, if the goal is to optimize access to daylight, a new design should be proposed which orients the patient's gaze in the direction of higher DA. It should be noted that, however, in real-world applications, users have low tolerance for glare. We tested (not included here) typical user window blind use on the circadian efficacy of daylight in a patient room, and found significant degradation when the blinds were lowered. This shows how important it is to include occupant behavior when analyzing the performance of a space.

Another factor in circadian-sensitive approaches to daylighting is the timing of bright light doses. This requires an understanding of the program of the space. In hospitals, patient rooms with both eastern and southern exposures will provide more constant illumination across most of the day, which may reinforce and the circadian entrainment and alerting effects of light in addition to enhancing a sense of orientation. In contrast, exposure only to bright light in the evening and not through the entire day may attenuate circadian entrainment, so avoiding west-facing rooms may be beneficial. For office spaces, bright midday light may enhance the sensation of alertness and improve performance during the workday. Temporal mapping will thus demonstrate which times of the day are the brightest from the office worker's perspective. The design of homes offers perhaps the finest gradient of temporal mapping opportunities, with program (i.e. bedroom) tied to timing of bright light exposure (i.e. morning) for the purpose of reinforcing circadian rhythm [1].

CONCLUSIONS AND OUTLOOK

The human circadian photoreception system differs anatomically and functionally from the visual system and therefore warrants specific consideration in the design of illuminated environments. This paper describes a new approach in integrating empirical data and findings in photobiology into the performance assessment of a space, thus combining visual criteria with health-related ones. The results of these simulations demonstrate how choices in building orientation, window size, user-window position, and interior finishes affect the circadian efficacy of a space. In each instance, design decisions can improve or degrade the health potential of the space considered.

For example, designs that intentionally capture light at key times of the day may reinforce the sense of health and wellness among building occupants. From these results, we demonstrate that even modest amounts of glazing can provide a high degree of circadian stimulus in certain orientations. Furthermore, while these findings are specific to the hospital patient room studied, the results can be applied to other building types such as office buildings and residences.

Current light simulation technology has little (RADIANCE) or no (DAYSIM) spectral modelling capability. Future research and development into a lighting tool that can simultaneously model intensity and spectra will certainly lead to breakthroughs in this research area. More accurate predictions of spectral distortions caused by reflections within a subject space will allow for better description of the space's circadian potential.

This paper does not conclusively correlate human health and daylighting, and the circadian photoreception function is only used as a proxy for human health effects in the absence of a more complete model of human health-light interactions. Contemporary research into circadian photobiology, however, provides us with important clues to one important physiological mechanism. We expound upon this mechanism in the hope that future environments will be healthier and more pleasant.

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DISCLAIMERS

The views expressed in this article are those of the author and do not reflect the official policy or position of the U.S. Air Force, Department of Defense, or the U.S. Government.

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