Elderly residents enjoy the sunlight at the Pozzoni Architects' designed Belong Wigan centre for people with dementia

Light, Health and Wellbeing:

Implications from chronobiology for architectural design

The design of health centres and other buildings needs to take into account the biological effect of light on different sectors of the population

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Chronobiology is the science of biological rhythms, more specifically the impact of the 24-hour light-dark cycle and seasonal changes in day length on biochemistry, physiology and behaviour in living organisms[1]. In the last 20 years, chronobiology has moved from its somewhat obscure scientific corner to a high-impact mainstream research field, notably with respect to the discovery of clock genes and peripheral oscillators – and a novel photoreceptor in the eye with specific input to the circadian system.

Key discoveries in human chronobiology are related to the impact of light. Recognition of the so-called 'biological effects of light' by lighting manufacturers has led to interest in developing new lighting systems that integrate this knowledge. Is it time for the medical mainstream to take notice of what neuroscientists know about the body clock? And is it also time for architects to do so?

These questions were explored at a symposium for architects, lighting engineers and manufacturers, initiated by Society for Light Treatment and Biological Rhythms (www.sltbr.org), in order to develop approaches to bridge the gap between these disciplines.

Main questions

Two timely questions to start this interdisciplinary discussion are:

• Do chronobiologists feel that their research has reached a point where clear conclusions can be drawn in terms of the drafting of design guidelines? Do they understand what architects and lighting engineers want?

• Do architects and lighting engineers feel that chronobiologists have provided enough information for them to be able to understand key principles and be in a position to evaluate how chronobiology might affect design?

On these issues, there is a marked difference in positions between the two groups taking part in the debate. The scientists, on the whole, remain cautious and circumspect, reluctant to draw hasty conclusions and to see them turned prematurely into design recipes. For them, the key questions seem to be; how can we obtain additional data? What type of further research is required?

Architects, lighting designers and manufacturers working within the realm of applied science are accustomed to working with imperfect and incomplete data; they are used to jumping in at the deep end, to cutting corners methodologically and to making 'live', full-scale experiments rather than conducting rigorously controlled laboratory research. We need to bridge the two cultures to find a compromise – to provide a short guide to chronobiology, however incomplete, that can be used as a design tool.

Radicality and urgency

The second set of questions concern the perceived magnitude of the potential impact and the urgency of the measures that may need to be taken.

• How radical could the impact of chronobiology be on architectural design?

• How urgent is it to look into this matter? Are we, through insufficient awareness of chronobiology, doing damage to people's health and wellbeing as a result of the way in which we design the built environment, not only so far as individual buildings are concerned, but also with respect to cities and urban landscapes?

On the above two questions, it is pertinent to draw a parallel with the impact that scientific research into global warming and environmental sustainability (also very cautious at first) has had on the disciplines dealing with the built environment and with the corresponding professional practices and industries.

It is clear that architecture and urban design, as well as lighting engineering, product design and manufacturing, have been profoundly affected in the last few years by the recent (albeit rather late) growth of awareness concerning the impact of the built environment on sustainability.

The majority of building regulations and product specifications have now been changed (or are in the process of being changed) to reflect changing priorities concerning the environment and the above listed disciplines have, as a result, been revolutionised in the span of a decade. The world around us, on all scales, from the design of lighting fixtures to the layout of cities, is changing rapidly.

Are we to expect a comparable design revolution once the criteria related to chronobiology are fully understood and embedded into practice?

Standards and regulations

The third set of questions relates to consensus:

• How close are we to being able to establish design standards related to chronobiological criteria?

• Would such standards lead to mandatory regulations or would they be laid down in the form of guidelines?

• How would they be implemented and monitored?

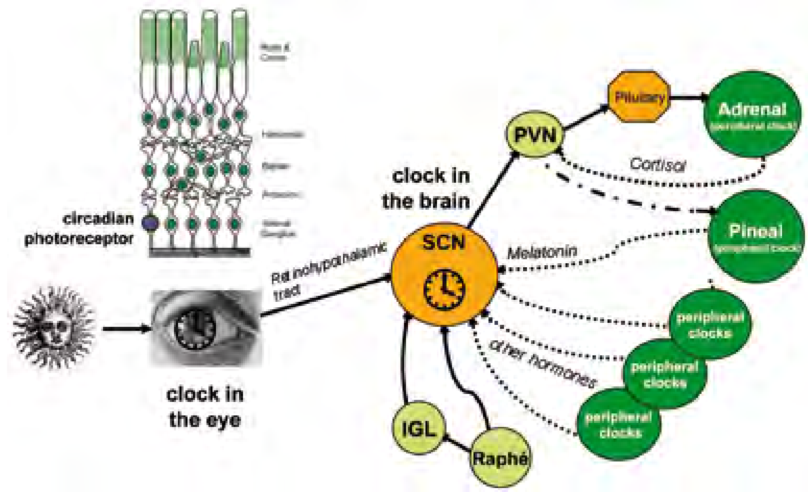

Figure 1: Schematic of the circadian timing system

The central circadian clock in the suprachiasmatic nuclei (SCN) drives downstream rhythms through neuronal output to the paraventricular nucleus (PVN) and hence to the pituitary (hormones) and the pineal gland (melatonin), and to peripheral organs (adrenal, liver, muscles, etc) which also contain circadian clocks. There are hormonal feedback loops to the SCN and direct neuronal input from other brain regions such as the raphé nuclei (which contain serotonin, a neurotransmitter implicated in mood and sleep regulation), and the intergeniculate leaflet (IGL) of the thalamus. A clock in the eye gates light input to the SCN via the retinohypothalamic tract. This pathway leads directly from the circadian photoreceptors in about 1-2% of the ganglion cells of the retina, which contain the photopigment melanopsin sensitive to blue wavelength light

Conflicting criteria

The fourth set of questions involves conflicting requirements. Design criteria related to environmental sustainability remained for a long time in sharp conflict with other criteria (and conventions) affecting design – in particular aesthetic criteria. 'Green architecture' was confronted with powerful taboos within sophisticated international architectural circles. Its connotations were perceived to lie with aesthetically mediocre, narrow-minded and reactionary design. Is this prejudice likely to raise its head again with respect to the design criteria that might emerge from a better understanding of the principles of chronobiology?

One of the main potential conflicts resides in particular with energy consumption:

• Would a greater awareness of the importance of chronobiology lead to higher levels of artificial lighting illumination and hence higher energy consumption?

• Could this be offset by design principles and guidelines calling for a greater use of natural daylight, and focused, timed, artificial lighting application?

• How can natural, endogenous biological rhythms – circadian and seasonal – be balanced with a 24/7 society where economic and social requirements take no notice of the geophysical environment?

With this broad set of questions in the background, the task is to integrate knowledge from the disparate disciplines. In order to understand the important implications of circadian rhythms for health and wellbeing, a brief summary of the state of our knowledge in chronobiology is required.

The human biological clock

The circadian timing system consists of a number of linked elements (Figure 1) (reviewed by Hastings *et al*[2]). Each of us possesses a biological clock in the brain. This central pacemaker is located in a group of about 20,000 neurones in the suprachiasmatic nuclei (SCN) of the hypothalamus, with an endogenous rhythm, genetically determined by our clock genes, close to, but not exactly, 24 hours. This does not mean that the biological clock is sloppy – the day-to-day precision is exact, but its periodicity is different from person to person.

The SCN sends neuronal output to various brain regions and target organs secrete hormones in a rhythmic pattern. Some hormones (such as melatonin synthesised by the pineal gland) can feed back on the central clock. Information from the environment is transmitted via recently discovered

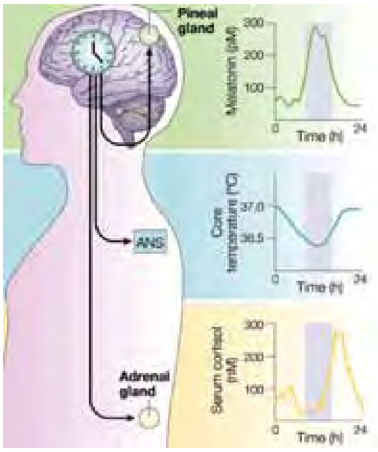

Figure 2: Schematic of selected outputs of the circadian timing system. The central circadian clock in the SCN, synchronised to the 24-hour day, drives rhythm in the periphery. Top: plasma melatonin rises in the evening before sleep and falls in the morning (and is suppressed by light). Middle: core body temperature shows a maximum in the afternoon and declines before sleep, rising after a late-night minimum in the early morning. Bottom: serum cortisol, low in the evening and early night, rises to a maximum before awakening. Reprinted by permission[2]

photoreceptors containing the novel photopigment melanopsin, which is most sensitive to the short-wavelength end of the visible spectrum light corresponding to blue and near-green light. These photoreceptors connect to a non-visual, retinohypothalamic tract leading to the SCN. Non-visual means that primarily information about illuminance and the light spectrum is transferred to the SCN. This is different from the classical photoreceptors (rods and cones) that connect to the optic tract leading to brain regions responsible for the sensations of colour, lines, movement and shape.

The existence of specific, highly conserved photoreceptors and a separate non-visual photic neuronal pathway to the brain of all mammals indicates the evolutionary importance of circadian rhythms for survival. Every measurable function shows a reproducible 24-hour rhythm, each with individual timing of maximum and minimum to optimise its particular role.

Rhythms that subserve a similar function cluster together synergistically; those that are antagonistic are separated in time, an admirably efficient solution.

Figure 2 illustrates this principle with three examples of SCN-driven rhythms in the periphery: the secretion of the pineal hormone melatonin during the night (suppressed by light); the output of the autonomic nervous system regulating temperature, which has an opposite rhythm to that of melatonin, being minimal at night; and the adrenal gland synthesising the activating hormone cortisol, low in the evening when sleep should begin, rising in the second half of the night to be maximal upon awakening[2].

The endogenous rhythm is called circadian because it is only 'circa diem' – with a periodicity near to, but not exactly 24 hours. Internal time must be entrained to the external 24-hour day with so-called 'zeitgebers' or synchronising agents. The most important zeitgeber for humans is light. Of course, social cues, meals and exercise all play a role and administration of exogenous melatonin has zeitgeber function.

How light acts as a zeitgeber

One of the basic tenets of chronobiology is that stable synchronisation (known as entrainment) is essential for health (Figure 3). The existence of multiple clocks throughout the body (Figure 1) means that the circadian orchestra needs a conductor to ensure good entrainment[3]. To permit optimum functioning, therefore, the SCN must first synchronise to the environment and oscillators in peripheral organs must follow. Not all zeitgebers synchronise the same clock(s). Light and melatonin are zeitgebers for the SCN. Exercise is a zeitgeber for muscles and meals are a zeitgeber for the liver. Since synchronisation of peripheral oscillators with each other and the SCN can be a slow process, sustained, regular 24-hour zeitgeber input is necessary.

The discovery in 1980 that light over 1000 lux was necessary to affect the human circadian system entirely changed our approach to light as zeitgeber (Figure 4)[4]. This is the outdoor light intensity as the sun comes over the horizon. The finding initiated the use of bright light to treat seasonal affective disorder or winter depression (standard treatment is now 10,000 lux for 30 minutes) and more than 25 years of research all over the world has documented that light is the treatment of choice for this illness[5]. In addition, light therapy has been used successfully to treat circadian rhythm sleep disorders so that individuals' internal time is better synchronised to external time[5].

Light at different times of day can have opposite effects on the biological clock. This is the principle of the 'phase response curve', which helps us adjust our endogenous circadian rhythms to environmental time cues. Light in the morning induces a phase advance (rhythms are shifted to earlier, as in a transmeridian flight east) and, in the evening, a phase delay (rhythms are shifted to later, as in a transmeridian flight west). In particular, light exposure at dawn and dusk are the most sensitive times to ensure good entrainment and require much lower light intensities for a physiological effect.

Chronotype

Clock genes are an important determinant of our endogenous circadian rhythmicity. Individuals vary greatly – and this leads to differences in timing of the sleep-wake cycle, otherwise known as chronotype[3]. Early chronotypes ('larks') and late chronotypes ('owls') may be well synchronised, but at different phases. In addition to a genetic determinant, chronotype changes with development[6]. Children are early birds, but at the beginning of puberty, their sleep-wake cycle starts shifting later and later. At about age 20 (the 'end of adolescence'), this developmental delay reverses slowly, leading eventually to the early morning awakening and early bedtimes of older persons.

Chronotype differences can lead to problems with getting up in time for school or work or inadvertently falling asleep in the early evening – or not being able to sleep when required. This difference between biological time and external requirements has been given the most appropriate name of 'social jet lag'[7].

Thus, one cannot advocate the same lighting requirements for teenagers and nursing home residents and one cannot assume a given timed lighting regimen is appropriate for individuals of different chronotypes working in the same office.

Circadian misalignment and health

When we measure with photometers over 24 hours how much light healthy people actually get, the results are somewhat disturbing; very few people, even in sunny climates, are outdoors sufficiently long enough to get their daily ration of sunlight for entrainment. Although indoor lighting (between 50-300 lux) is perfectly adequate for the visual system, it is near darkness for the circadian system. The human species evolved to function with more than one hour of daylight per 24 hours – but now in industrialised nations we appear to receive too little light during the day and too much light at night.

Is the increase in mood and sleep disorders related to unnatural lighting patterns? It is clear that more and more people's working and social lives are disrupted by skewed sleep patterns. And little respect is paid to the light-dark environmental cycle by a society demanding shift work and inflexible work and school times in winter and summer[1].

There is some evidence, gathered in extreme medical environments (intensive care units, neonatal units, paraplegic centres and nursing homes), that a natural light-dark/day-night cycle is important for health and recuperation.

Architecture-related findings show that outcomes in a cardiac intensive care unit after a heart attack are better in sunny rooms compared to dull rooms, with lower mortality[8]. Similarly, hospitalised patients with depression improved approximately three days faster when admitted to brighter rooms than in rooms receiving less daylight[9,10]. In fact, by installing brighter lights on a psychiatric ward, depressed patients had a three-day-shorter duration of hospitalisation[11]. Increasing light intensity in the day-rooms of nursing homes where demented patients spend most of their time has also been shown to slow down the rate of cognitive decline and improve depressive mood when compared with demented patients living under normal lighting regimens[12].

Most of the evidence base for the therapeutic effect of light has come from treating mood and circadian rhythm sleep disorders. These unequivocal findings in both seasonal and non-seasonal depression, and in a variety of psychiatric and neurological disorders, provide the clinical evidence that structured light exposure – intensity, duration and timing – is therapeutic. Thus, the logical follow-up to putatively prevent these illnesses is to pay attention to daily light regimens and consider adequate light exposure as a major factor underlying health and wellbeing.

Integration and practice

Given the above summary of circadian rhythm function in humans, what are the next steps in implementing this knowledge in the development of a more 'physiological' architecture?

What are, within the disciplinary fields related to the built environment, as well as the corresponding professional practices and industries, those that might be affected by the growing awareness of the importance of chronobiology? Might the range of the affected fields be as comprehensive as that resulting from the priority that was eventually given to environmental sustainability?

These fields potentially include the following:

- product design
- interior design
- lighting design and engineering
- architecture
- urban design
- landscape design
- city planning
- transportation engineering
- utilities engineering
- building sciences

Within each of these fields, is there a sufficiently detailed understanding of the possible impacts?

Research cooperation

What type of joint research projects could be envisaged between scientists and architects/lighting designers to explore this topic further? What form could such a cooperation take?

People working in the building sciences tend, by nature as well as by necessity, to proceed by trial and error within the messy conditions of the 'real world', dealing with many parameters simultaneously, while scientists seek to isolate variables in controlled environments. Would it be feasible to bring the two together in the context of experimental projects that would explore the application of chronobiology to architecture?

What type of projects could be envisaged, and at what scale? Is it feasible to envisage the design of a prototypical 'circadian house' (workplace, hospital, etc) that would seek to address comprehensively the key principles of chronobiology?

Much can be learned from case studies of projects that have already been realised, particularly within medical establishments, schools, workplaces and retirement homes. The successful home use of light therapy by individuals with circadian rhythm sleep and mood disorders has supported the premise of an important relationship between the built environment, light-oriented behaviour and healthy functioning.

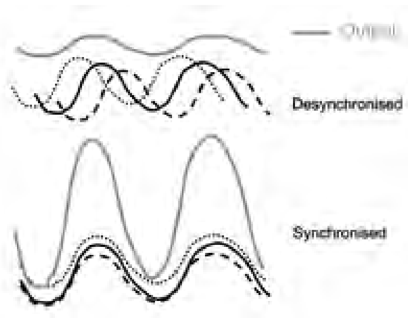

Figure 3: Schematic of how zeitgebers stabilise circadian rhythms. Coupling central and peripheral rhythms to the 24-hour day results in a high amplitude rhythm which is stable. A low amplitude rhythm is more easily shifted and less reliable day to day

Draft guidelines

We already have a few simple guidelines, though as yet without any detailed recipes.

- Homes and workplaces may need to achieve higher intensity light at certain times of day, without compromising visual comfort. However, this is not required in all parts of the room (energy dissipation) but rather near the eye of the individual. Different chronotypes will require personalised regimens.
- Specific requirements of different age groups need to be taken into account. Adolescents and young adults have a somewhat delayed biological clock and have difficulty getting up in the morning. They would profit from bright morning light as soon after getting up as possible (at the breakfast table) or dawn simulation in the bedroom. School rooms may be too dark in the morning and require a luminous burst for the first hour. In contrast, older persons have a biological clock that has shifted earlier (often resulting in falling asleep in the evening and in early morning awakening). Evening light in their preferred environment may help them stay awake until a later bedtime.
- This higher intensity light should be achieved, as far as possible, through the use of natural daylight, because of the higher levels of illumination that it offers, compared to artificial light, as well as its other zeitgeber cues: varying levels of illumination, colour temperature and sun orientation during the course of the day, from dawn to dusk. The twilights themselves are biologically active and span seven orders of magnitude below sunrise level. We need to use and extend 'intelligent' and effective daylighting systems.
- Internal spaces within buildings, should, as far as possible, be designed in such a way as not to obstruct the entrainment cues offered

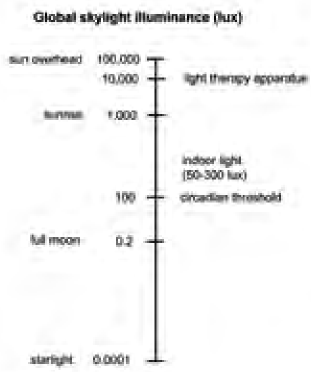

Figure 4: Range of daylight intensities visible to the human eye

by the natural environment, particularly in terms of the direction and azimuth of the sun, by minimising overshadowing and allowing distant views.

• The most common design example is the customary placing of bedrooms towards the east, so that the orchestration of early morning light conditions within the home can be in phase with the corresponding physiological timing of waking up. It may be beneficial to apply this synchronisation principle to other activities that take place on a regular basis within the home and other buildings, such as food preparation and meals, different kinds of work and educational activities, as well as leisure activities.

• In conditions where insufficient daylight penetration occurs within a building, the design of artificial lighting should seek, as far as possible, to simulate the key characteristics of natural light with respect to those variables that are significant for chronobiology.

• The spatial planning of land uses within the urban fabric should be considered with a view to fully experience the circadian and seasonal periodicities of the natural environment.

• The discovery of the blue-sensitive melanopsin-containing photoreceptor and studies showing that monochromatic blue light is more efficacious than, for example, monochromatic green light to suppress melatonin, phase-shift circadian rhythms and enhance alertness and performance has led to rapid development of high colour temperature lighting devices. These have been installed in schools, nursing homes, and offices, with some indication of improved function of the inhabitants of these rooms in short-term studies.

However, the circadian system is not quite so simple. Recently, it has been shown that red light can sensitise the melanopsin photoreceptor to enhance melatonin suppression and phase shifting. Thus, the cones that subserve daytime visual sensory function also play a role.

Almost surely, dynamic lighting systems of the future will programme different colours for different purposes (enhancing vigilance or helping to fall asleep) in a particular sequence and in different intensities. We do not yet know enough of the specifics of this complex system. Already existing multicolour lighting devices on the market are based on insufficient circadian know-how to be used properly.

• Buildings are already equipped with numerous timekeeping devices and sensors designed to adjust various parameters of the internal environment during the daily cycle, particularly to control temperature variations via thermostats and timers. Responsive systems are also used to control lighting conditions, but until now they have not been so common. It will be necessary to ensure that buildings are fully informed, via photosensors, of the lighting conditions within their interior environment as well as the exterior and to monitor occupancy conditions.

• Artificial light sources, both within public places and private spaces, should be designed and placed so they minimise the amount of light pollution at night, in order to achieve adequate darkness conditions in residential areas within the city and in sleeping areas within the home. Darkness is an important determinant of circadian adjustment, as is the gradual twilight transition from darkness to daylight.

This summary of questions and discussion topics at the Society for Light Treatment and Biological Rhythms meeting are to be considered the beginning of a dialogue to improve quality of life through careful lighting and building design in everyday home, work and hospital environments.

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