Embracing Biological Needs in Lighting Design

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ARUP

Goals of Lighting Design?


The beautiful light.


The green light.

The best functional light.

Goals of Lighting Design

1. Beautiful built environments
2. Energy efficient design
3. Functional lighting

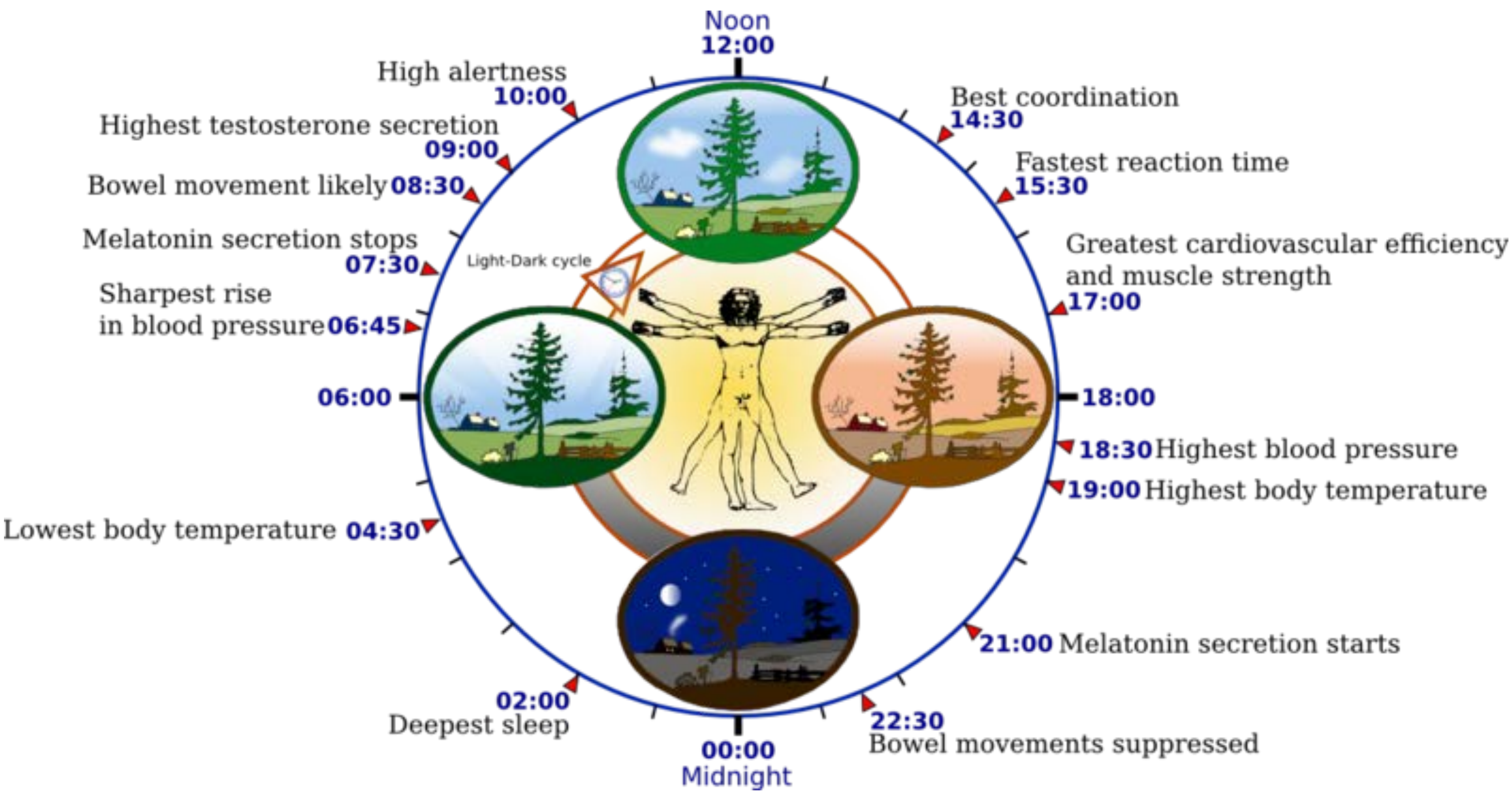
Integration of daylight

4. Promote human health?

Is This Realistic?

1. What we know
2. What we don’t know
3. We might know
4. What we “know”

What We Know



Noon
12:00
High alertness
10:00
Highest testosterone secretion
09:00
Bowel movement likely 08:30
Melatonin secretion stops
07:30
Light-Dark cycle
Sharpest rise
in blood pressure 06:45
06:00
Lowest body temperature 04:30
02:00
Deepest sleep
00:00
Midnight
Best coordination
14:30
Fastest reaction time
15:30
Greatest cardiovascular efficiency
and muscle strength
17:00
18:00
18:30 Highest blood pressure
19:00 Highest body temperature
21:00 Melatonin secretion starts
22:30
Bowel movements suppressed

Example

WK: Daylight views help hospital patients recover ~25% faster

DN: visual connection, access to full spectrum light, quantity of light, dynamic white?

MK: Daylight access helps patients sleep better

Example 2

MK: Exposure to light at night has been linked to several types of cancer (breast, prostate), diabetes, heart disease, and obesity

DN: too much!

http://www.health.harvard.edu/staying-healthy/blue-light-has-a-dark-side

What We “Know”

http://www.cell.com/current-biology/abstract/S0960-9822%2813%2900764-1

With Chromaticity Control..

Research Needs More Applied Projects

Interview by Tom Avril
Published: July 24, 2012

Lighting & Health
A longitudinal Study (2007)

Background

Photopic + Scotopic eye sensitivity curves

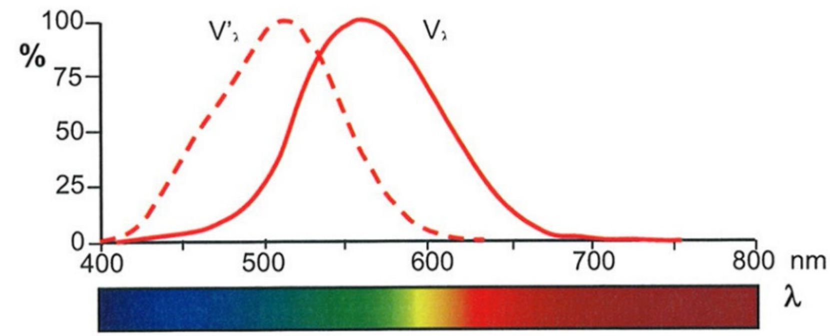


Fig. 2 Spectral eye sensitivity curves, V_λ for the cone system (photopic vision: solid line) and V'_λ for the rod system (dotted line).

Photopic + Biological eye sensitivity curves

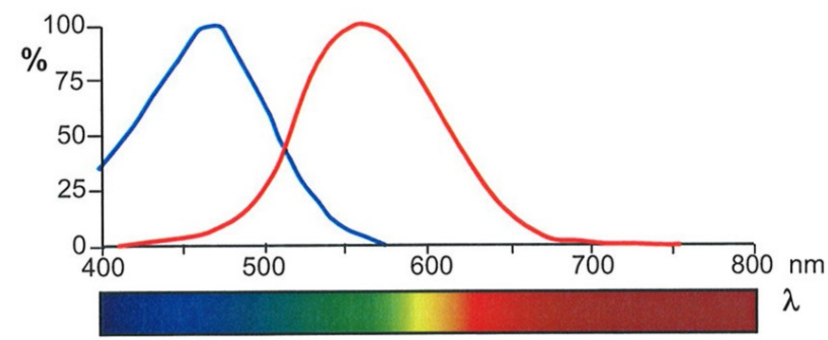
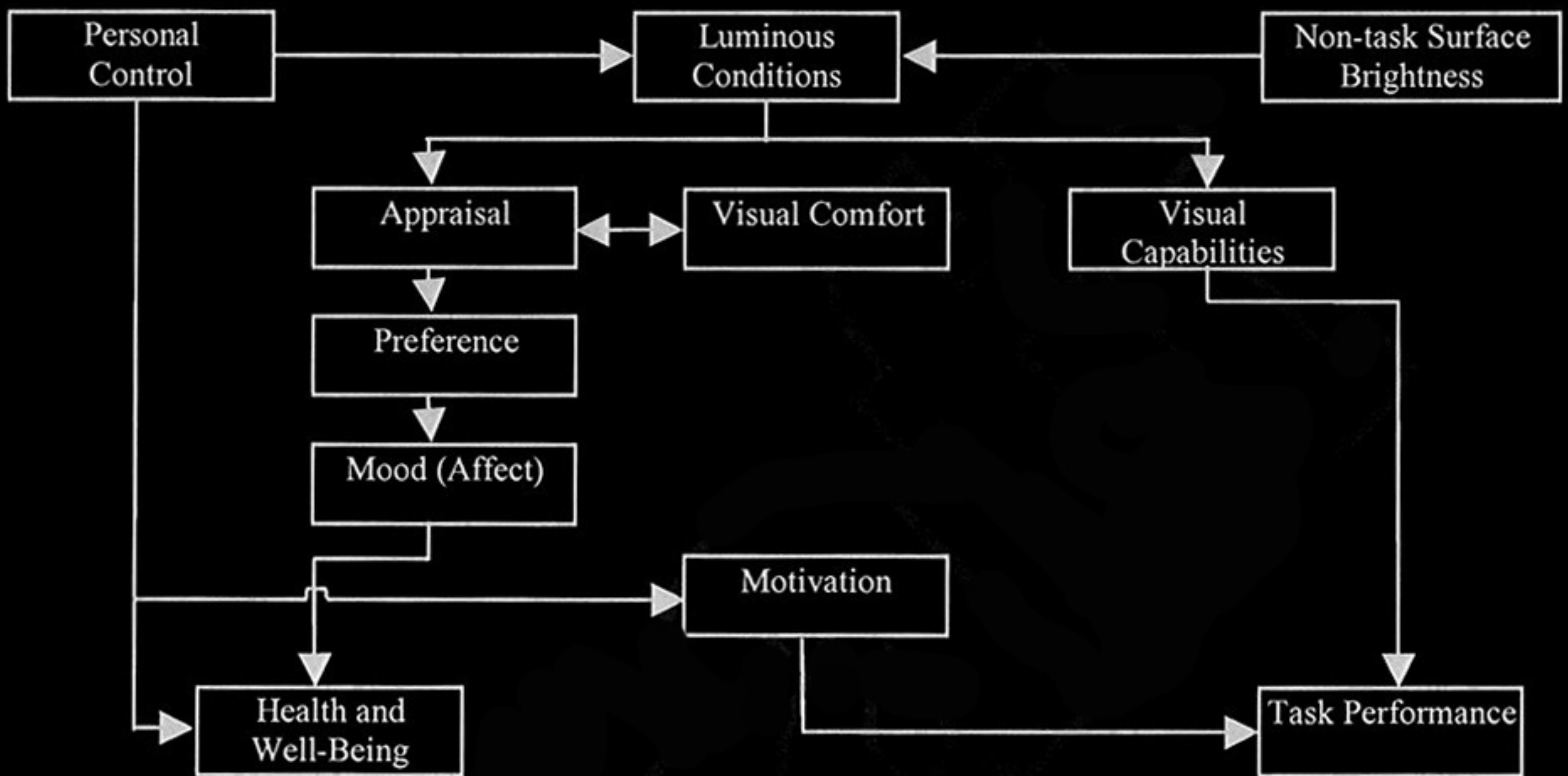


Fig. 3 Spectral biological action curve (based on melatonin suppression), in blue, (source: Brainard [6]), and the visual eye sensitivity curve, in red. [Philips Lighting]

Linked Mechanisms

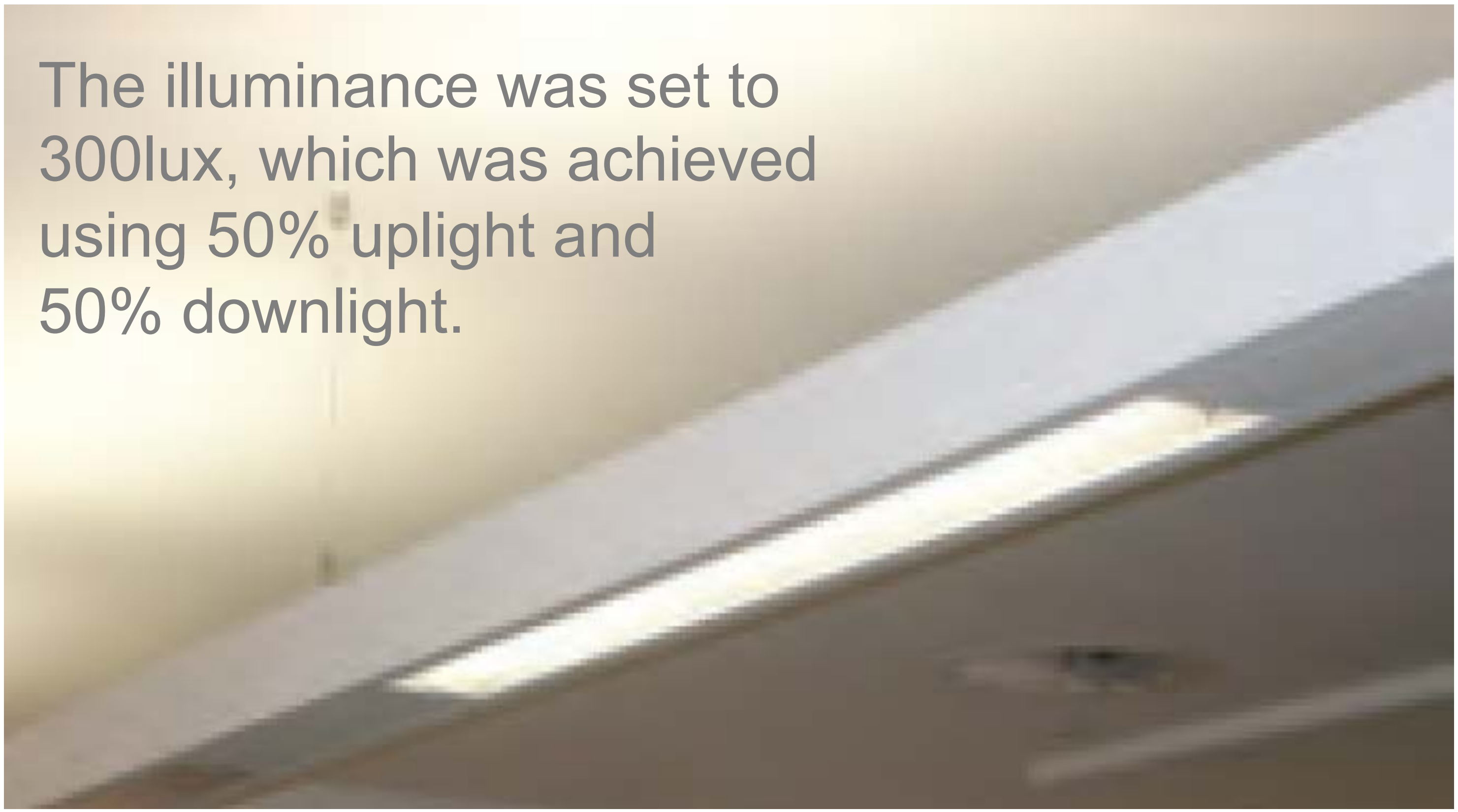


Linking luminous conditions to health, well-being and performance (Boyce et al, 2006)

Aims

- Examine the impact of lighting on productivity, wellbeing and other measures of organisational effectiveness
- Determine the impact of “blue-white” light as a means of enhancing performance and wellbeing
- Investigate whether the positive effects of lighting can be realised in a “real” world field setting.

Lighting System

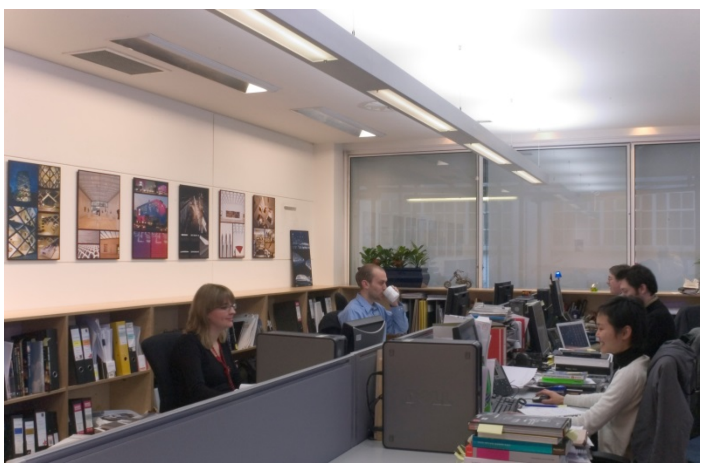


The illuminance was set to 300lux, which was achieved using 50% uplight and 50% downlight.

Lighting Conditions

Daylight + 3000K

4000K



4000K + 17000K

17000K

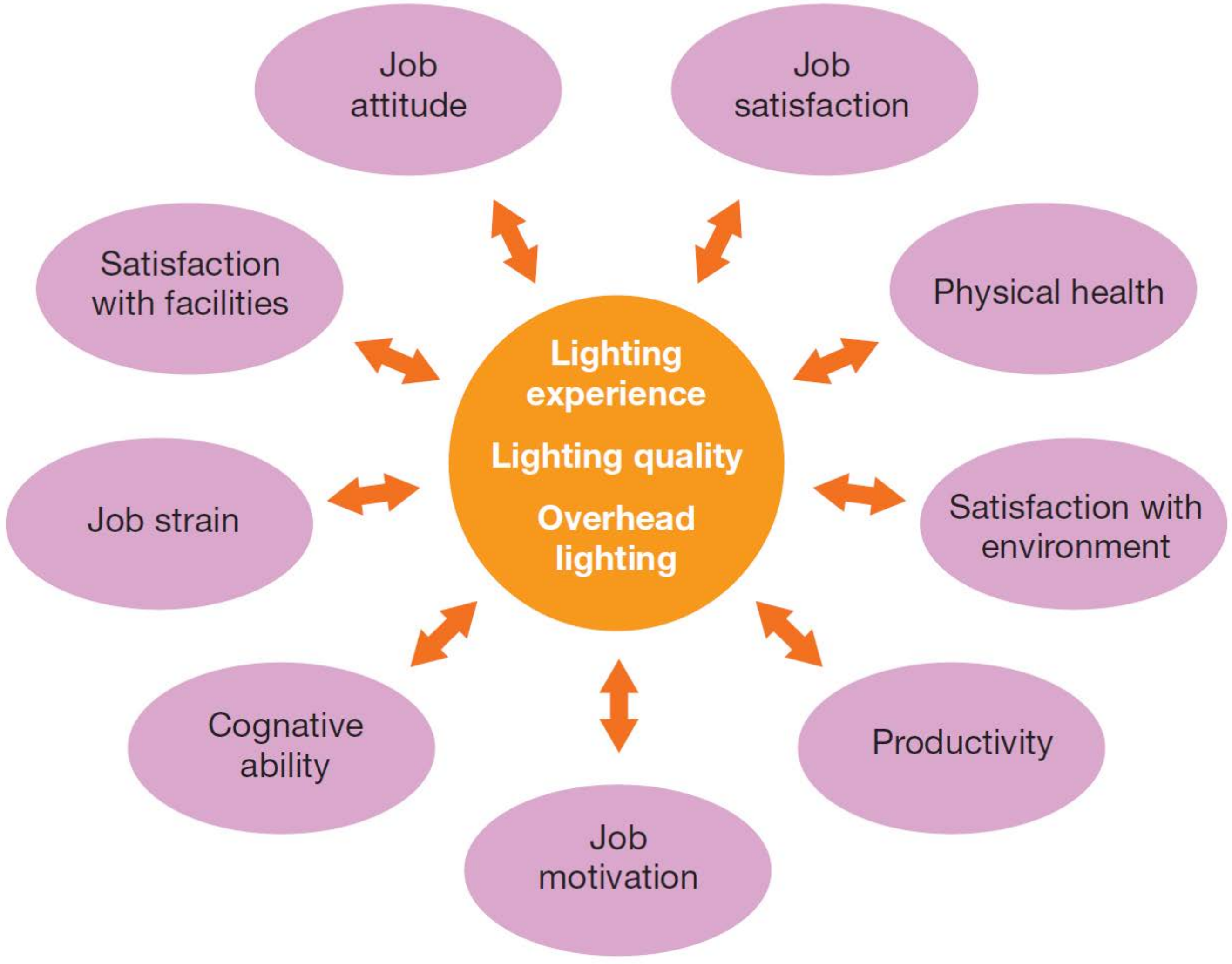
Lamp Rotation

One lamp was changed every six weeks, resulting in eight lighting changes throughout the duration of the research.

Table 1. Lamp rotation.

Time	Lamp1 up	Lamp 2 up	Lamp 3 down	Season
Period 1	4000K	4000K	4000K	winter
Period 2	4000K	17 000K	4000K	spring
Period 3	17 000K	17 000K	4000K	spring
Period 4	17 000K	17 000K	17 000K	summer
Period 5	4000K	4000K	4000K	summer
Period 6	4000K	17 000K	4000K	autumn
Period 7	17 000K	17 000K	4000K	winter
Period 8	17 000K	17 000K	17 000K	winter

Key outcome variables



Significant findings

- The "blue-white" light did have an impact on productivity, wellbeing, and the other measures of organisational effectiveness.
- Lighting experience ⬄ Job Motivation ⬄ Job Attitude ⬄ Productivity
- All "blue-white" light made sleeping difficult at night
- (17 000K) indirect (up) lighting and warm (4000K) direct (down) lighting was favoured equally with the traditional all warm (4000K) light.
- Some of the indicators, however, showed slightly improved performance over the all 4000K lamps.

Circadian Rhythm Lighting in Commercial Applications

Literature Review 2014

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Considerations for lighting in the built environment: Non-visual effects of light

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Abstract

Light is defined as that part of the electromagnetic spectrum (~380–780 nm) that gives rise to a visual sensation. Lighting in buildings, whether through use of daylight or by artificial means, is designed primarily for the visual needs of the occupants and their expected tasks within a given space. However, solar radiation, and, depending on spectral output of the source, artificial radiation, has other effects on human physiology and behaviour. Blue light affects the circadian rhythm, mood and behaviour; at shorter wavelengths in the ultraviolet (UV) the detriments of photoaging and sunburn are balanced by the benefits of Vitamin D synthesis.

Keywords: Daylighting; Melatonin; Circadian rhythm; Ultraviolet; Vitamin D; Erythema

1. Introduction

Buildings, by their nature, create an artificial environment that differs from the ambient conditions outdoors. They provide shelter from wind and rain and the extremes of heat and cold, and are often equipped to provide controlled comfort levels of heat and humidity. Buildings also have internal lighting, to compensate for the restricted natural light that can penetrate the structure, and to allow the occupants to function at all times of day or night. The primary concern in the lighting of buildings has generally been to allow for vision, suited to the room or building usage. However, light has other implications for our health and well-being which merit consideration in the lighting, and use of daylighting, within buildings.

2. Spectral characteristics of daylight and artificial lighting

The source of daylight is the sun. The extraterrestrial solar radiation, approximated by blackbody radiation at 5800 K, is modified as it passes through the atmosphere, losing the shortest wavelengths so that the spectrum at the ground begins in the UVB region (280–315 nm). There is also loss in other wavebands, especially the infrared, due to absorption by water vapour, carbon dioxide and other atmospheric constituents. Fig. 1 shows a typical ground level solar spectrum, peaking in the visible region (400–700 nm) of the electromagnetic spectrum. This is the natural radiation environment within which we evolved, with vision that is most efficient at wavelengths from blue (400 nm) to red (700 nm), although both shorter, UVA, and longer, infrared, radiation can be detected by the human eye in the right circumstances [2].

The intensity of solar radiation, and its spectral shape (particularly in the UV) varies with solar elevation, controlled by latitude, season and time of day. Solar radiation is far from constant, but the hours of daylight and the diurnal variation are very predictable at any location and season. A secondary influence is the weather since cloud can greatly reduce solar radiation at the surface, albeit in a transient and unpredictable way.

Artificial lighting provides a consistent radiation field that can simply be turned on or off. However, it has rather different spectral characteristics to the sun, directed towards allowing suitable visual performance in a simple and economic fashion [3]. Fig. 2 shows the spectra of some typical indoor light sources, a tungsten filament lamp and fluorescent lamp. Note that the tungsten lamp spectrum increases towards the red end of the spectrum and has a large infrared output as well, while the fluorescent lamp peaks at shorter wavelengths, giving the tungsten filament lamp a softer looking more yellow light when

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A higher illuminance induces alertness even during office hours: Findings on subjective measures, task performance and heart rate measures

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ABSTRACT

Nocturnal white light exposure has shown marked results on subjective and objective indicators of alertness, vitality and mood, yet effects of white light during daytime and under usual office work conditions have not been investigated extensively. The current study employed a mixed-group design (N = 32), testing effects of two illuminance levels (200 lx or 1000 lx at eye level, 4000 K) during one hour of morning versus afternoon exposure. In four repeated blocks, subjective reports, objective performance and physiological arousal were measured. Results showed effects of illuminance on subjective alertness and vitality, sustained attention in tasks, and heart rate and heart rate variability. Participants felt less sleepy and more energetic in the high versus the low lighting condition, had shorter reaction times on the psychomotor vigilance task and increased physiological arousal. Effects of illuminance on the subjective measures, as well as those on heart rate were not dependent on time of day or duration of exposure. Performance effects were most pronounced in the morning sessions and towards the end of the one-hour exposure period. The effect on heart rate variability was also most pronounced at the end of the one-hour exposure. The results demonstrate that even under normal, i.e., neither sleep nor light deprived conditions, more intense light can improve feelings of alertness and vitality, as well as objective performance and physiological arousal.

1. Introduction

At work, people may experience fatigue and a depletion of mental resources. These increased feelings of sleepiness, lack of energy, psychological stress and decrements in performance may be the result of an accumulation of effort spent throughout the working day and of homeostatic and circadian regulation of sleep and wakefulness [1,2]. In this study, we investigate whether office lighting, and in particular the amount of light, i.e. illuminance, at eye level can improve office employees' alertness, vitality and performance during daytime.

Research has established that light can have both direct and phase shifting effects on the circadian clock [3,4]. Direct effects of light on the human nervous system refer to instantaneous changes in physiological arousal, while phase shift effects refer to temporal changes in the circadian rhythm. In addition to these physiological effects, studies have shown that exposure to higher illuminance levels can result in feelings of increased alertness and better performance [5–12]. Importantly, most of these studies have assessed the effect of nocturnal light exposure on physiological and psychological measures of arousal and alertness. Moreover, the scarce diurnal data come from studies in which subjects were first substantially sleep and/or light deprived [10,12,13]. In contrast, little is known about such effects under the conditions many of us live and perform in: during daytime, under normal (or close to normal) sleep pressure, and without hours-long pre-treatment exposure to darkness. Under such conditions, effects may be less pronounced or even disappear altogether, as alertness levels and brain activity may already be optimally tuned to daytime performance, hormonal levels of cortisol and melatonin are already in phase with task demands, and some may already have had substantial amounts of daylight while commuting or during a coffee or lunch break. Although controlled tests of illuminance levels under natural daytime conditions are scarce, a few recent studies do suggest effects of blue-enriched or high correlated colour temperature (CCT) lighting [14–16].

As one exception, Badia and colleagues investigated the effect of illuminance on physiological arousal, subjective alertness and task performance during night time, but also during daytime without sleep deprivation or prior exposure to low illuminance levels [17]. Results revealed night-time effects of illuminance level on alertness, body temperature, EEG and performance; in contrast, the results in the afternoon showed a comparable, but non-significant trend. It should be noted, however, that the number of participants in this particular study was relatively low (N = 8). A field study employing fairly

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Literature Review

Journal references:

No	Title	Page	Experiment	Object	Time	Duration	Findings	LUX	CCT
1	Healthcare Forum	p.33-34	Office w/direct expose to skylight	<10ppl M/F	dawn-dusk	NA	Daylight exposure increases productivity and **shorten recovery cycles**	250-2800	3900-4050
2	Light staff well-being and performance	p.12	Office w/window daylight	NA	NA	3 mths winter	Daylight exposure **increase productivity in assumption ppl get enough daylight to regulate their circadian rhythm**	**73-1105**	daylight
2a		p.13 p.13 p.14	Office w/window daylight&artificial Summary Summary	29ppl NA NA	12.00-20.00 NA NA	2 days NA NA	Daylight exposure increases the alertness, better cognitive performance, **lower sleepiness** Daylight exposure **decrease light sensitivity during night time result in entrain the melatonin hormon** **Circadian system sensitivity will change depend on previous light exposure/contrast between night and day**	1000 NA NA	daylight NA NA
3	A higher illuminance induces allertness even during office hours	p.7-8	Lab study w/o window	8ppl	office hours	NA	Brighter light didn't indicate alerting or vitalizing. Studies suggest high CCT expose during daytime.	300/700	3900-4700
3a		p.8-15	Lab study w/o window	32ppl	9.00-10.30or 11.00-12.30or 1.00-2.30or 3.00-4.30	NA	Monochromatic light exposure (blue vs green) influences emotional brain processing **One hour higher illuminance exposure during daytime relate to allertness,vitality,** performance, heart rate and HRV	**200/1000**	4000
4	An experimental study on improvement of office work productivity by circadian rhythm light	p.1	Lab office w/ high illuminance	15ppl	NA	18 days	One hour high illumination exposure in the morning to enhance arousal level in daytime to **improve sleep quality by night time** Standard illumination exposure after that good for preparing nap time One hour high illumination after lunch exposure to prevent sleepiness Standard illumination exposure to prevent fatigue for the next day	**1000-500(am)** **1000-700(pm)**	5500 5500
5	An hour of bright white light in the early morning	p.146	Research lab	9ppl	8.30-9.30	3 mths winter	One hour high illumination exposure in the morning benefits in in advancing circadian phase	**2500 (1hr)**	NA
5a		p.147	Research lab	9ppl	8.30-9.30and nightshift	6weeks	One hour high illumination exposure in the morning result imroved sleep and alertness	**4775/1050 (1hr)** **731-445 (the rest)**	NA
6	Circadian rhythms opinion paper	p.4	Summary	NA	NA	NA	CW appropriate for morning to mid afternoon for **wake cycle**, WW for afternoon early evening for **entrain cicadian rhythm**	NA NA	3500-6000 (am) 2700-3000 (pm)
7	Field study of office worker responses to fluorescent lighting	p.70-73	Office w/ and w/o window	26ppl	office hours	2 weeks	Warmer color is generally preferred. With and without daylight exposure warmer and bright lighting is preferred. Cooler color and brighter light create more glare. Cooler color works with dimmer lighting Experiment relate to visual comfort, overall satisfaction, and work performance. No mention abt circadian rhythm.	2330/3000lm	3500/5000
8	Illuminating the effects of dynamic lighting on student learning	p.6-9	Classroom with minimal daylight	84ppl	NA	3 times/year	Lighting qualities of ilumination and CCT influence student gains in reading.	**1000**/500	6000/3500
9	Lighting affects students' concentration positively findings	p.1 p.1 p.1	Classroom Classroom Classroom lab w/ control system	89ppl 37ppl 55ppl	NA NA NA	winter and spring 1mth 6week	Environment in which different lighting settings and conditions are used to support the specific activities and task maybe more effective for pupil learning than an environment with the same lighting condition exposure.	**350-1000**	3000-12000
10	Lighting does matter preliminary assessment on office workers		Office lab w/ 3CCT (WW,CW,DL)	10ppl	NA	1week	CW is comfortable, good for typing and eye fixation	400	2700/4000
10a			Office lab w/ 3CCT (WW,CW,DL)	10ppl	NA	1week	DL is generally **prefered** WW good in alertness at the beginning and end of the day.	400	2700/6200
11	Mechanisms involved in enhancing human performance	p.7	Summary	NA	NA	NA	Mood and lighting is subjective.	2500	NA
12	Occupant preferences and satisfaction with the luminous environment	p.734	Office with lighing control automatic mode	NA	NA	NA	High illuminance levels preferred	NA	NA
12a		p.734	Office with lighing control semi-automatic mode	NA	NA	NA		NA	NA
12b		p.734	Office with lighing control manual mode	NA	NA	NA		NA	NA
13	Osram Light in its third dimension	p.7,14-15	Summary	NA	NA	NA	**Positive biological effect achieved by wide area lighting in the upper field of view**	NA	3000-8000
14	Study 3 technical paper	p.3	Summary	NA	NA	NA	Lesser brighness relate to warmer CCT **Link to natural daylight**. Day time refer to cold light, sunset to warm light. CCT: day >4000K night <4000K In the present of computer lower light level should be provided. 300-500lux on the task	300-500	>4000 (am) <4000 (pm)
15	The effect of high correlated colour temperature office lighting	p.2-3	Office w/window and blinds	NA	08.00-20.00	NA	High CCT improves wellbeing, functioning and work performance	NA	NA

Summary on Review Findings

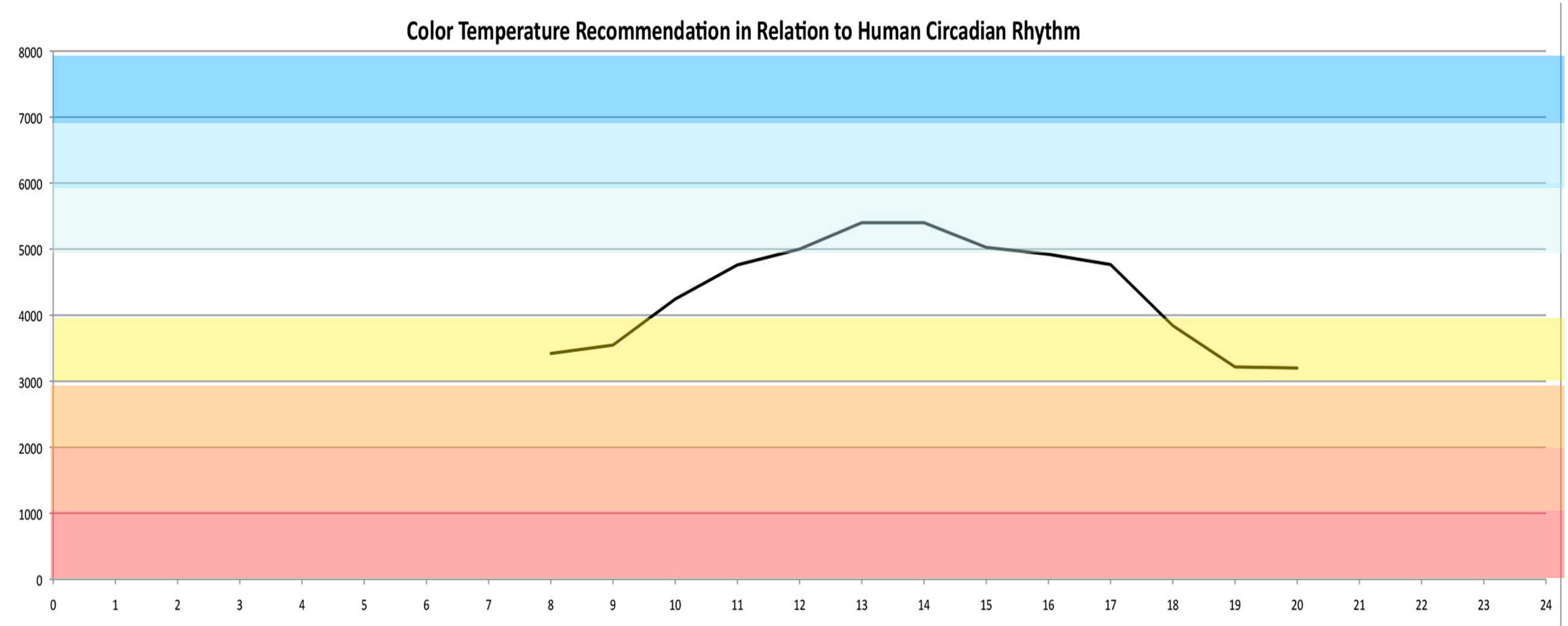
Brightness recommendation in relation to Human Circadian Rhyth

Brightness (lux) -assumed on the workplane *on eye level	>2500									2925*(5a)				2800*(1)											
	2500									2500*(5)(16)	2500*(16)		2250*(1)	2500*(16)	2500*(16)										
															2250*(1)										
	2000											1850*(1)				1850*(1)									
	1500										1450*(1)						1450*(1)								
	1000									1050*(1)								1050*(1)							
										1000*[illegible]	1000*(5)(5a)	1000*(16)		1000*[illegible]		1000*(16)									
												750*(5)	750*(16)				750*(16)	750*(16)	750*(16)	750*(16)					
												668*(5a)	668*(5a)	668*(5a)	668*(5a)	668*(5a)	668*(5a)	668*(5a)	668*(5a)	668*(5a)					
	500														700*[illegible]	700*[illegible]	700*[illegible]	700*[illegible]	650*(1)						
													600 (14)	600 (14)	600 (14)										
											500*[illegible](14)	500*[illegible](14)	500*[illegible](5)	500(5)	500(5)	500(5)(14)	500(5)(14)	500(5)(14)	500*(5)[illegible]	500*(5)[illegible]					
	300																								
										300 (14)									300(14)	300(14)					
	200																			250*(1)					
	100																								
	<100																								
Time of the day (hr		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Human Circadian Rhythm			02.00 deepest sleep		04.30 LOWEST BODY TEMPERATURE		6.45 SHARPEST RISE IN BLOOD PRESSURE	7.30 MELATONIN SECRETION STOPS	08.30 BOWEL MOVEMENT LIKELY	09.00 HIGHEST TESTOTERONE SECRETION	10.00 HIGH ALERTNESS				14.3 BEST COORDINATION	15.30 FASTEST REACTION TIME	17.00 GREATEST CARDIOVASCU-LAR EFFICIENCY AND MUSCLE STRENGTH		18.30 HIGHEST BLOOD PRESSURE	19.00 HIGHEST BODY TEMPERATURE		21.00 MELATONIN SECRETION	22.30 BOWEL MOVEMENT SUPPRESSED		

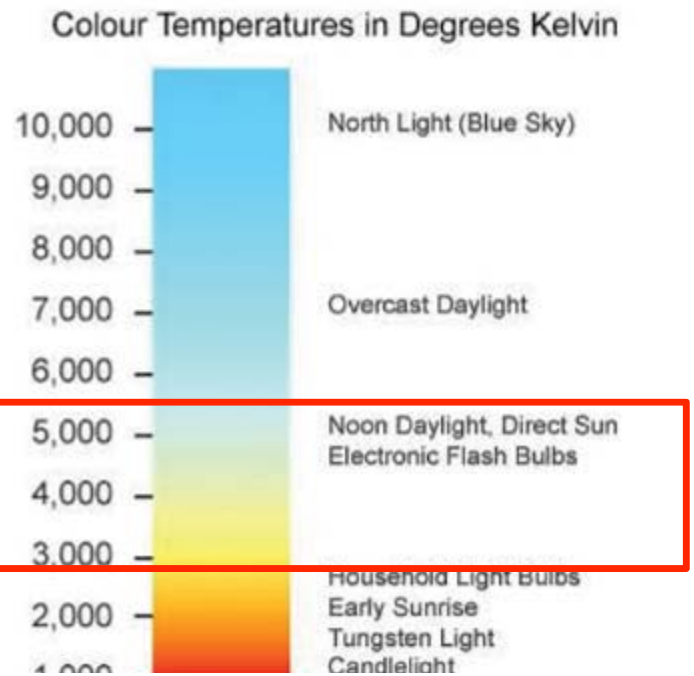
Color Temperature recommendation in relation to Human Circadian Rhythm

Color Temperature (K)	9000																								
	8500																								
	8000													8000 (13)											
	7500																								
	7000												7000 (13)		7000 (13)										
	6500																								
	6000										6200(10a)	6000(10a)(13)	6200(10a)	6000 (6)(10a)	6200(10a)	6000(10a)(13)	6200(10a)	6200(10a)							
	5500												5500(6)	5500(14)	5500(6)										
	5000										5000(13)	5000 (6)	5000(14)		5000(14)	5000(6)	5000(13)								
	4500									4500(13)		4500(14)						4500(13)							
	4000										4050 (1)	4050 (1)	4050 (1)	4050 (1)	4050 (1)	4050 (1)(14)	4050 (1)	4050 (1)							
									4000(13)	4000 (1)(6)	4000 (6)(10)(14)	4000 (10)	4000 (10)	4000 (10)	4000 (10)	4000 (10)	4000 (10)(6)(14)	4000 (10)	4000(13)(1)						
									3900 (1)											3900 (1)					
	3500								3500(6)	3500(14)								3500(14)(6)							
	3000								3000(14)										3000(6)(14)	3000(13)					
	2500								2700 (10)(10a)	2700 (10)(10a)									2700 (10)(10a)	2700 (10)(10a)(14)(6)					
	2000																								
	1500																								
	1000																								
Time of the day (hr		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Human Circadian Rhythm			02.00 deepest sleep		04.30 lowest body temperature		6.45 sharpest rise in blood pressure	7.30 melatonin secretion stops	08.30 bowel movement likely	09.00 highest testoterone secretion	10.00 high alertness				14.30 best coordination	15.30 fastest reaction time	17.00 greatest cardiovascu-lar efficiency and muscle strength		18.30 highest blood pressure	19.00 highest body temperature		21.00 melatonin secretion	22.30 bowel movement suppressed		

Colour Temperature Findings



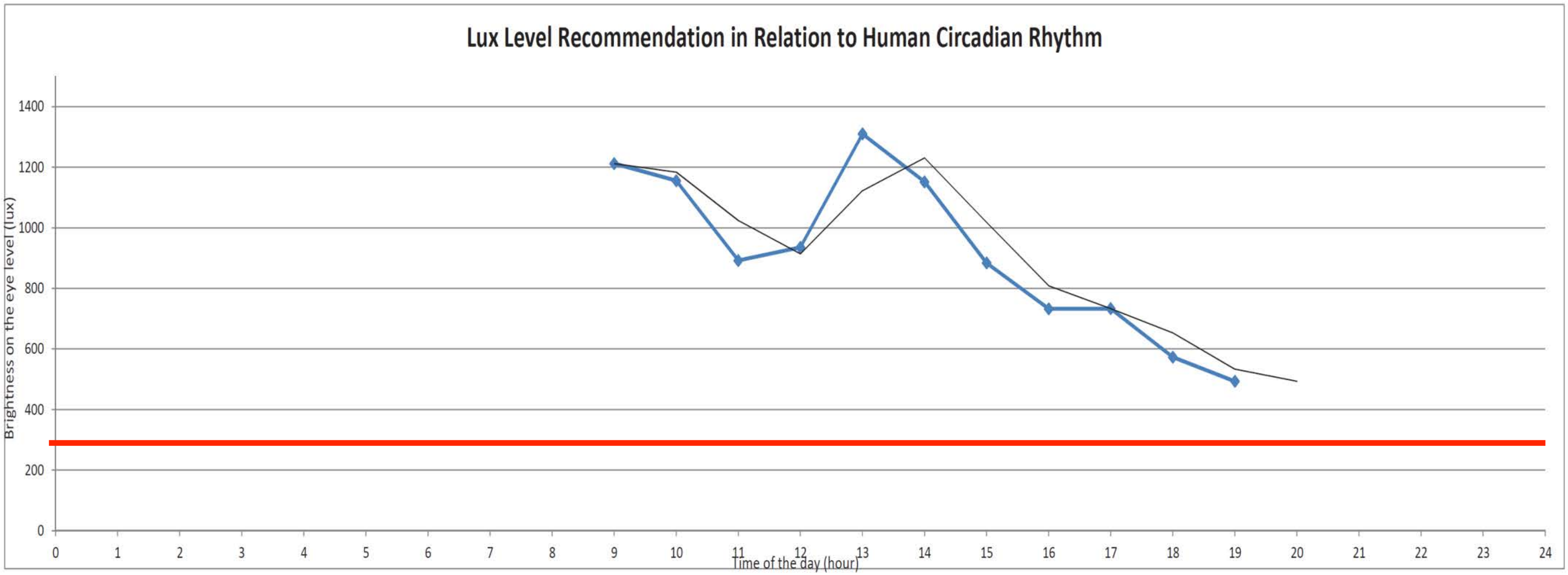
Colour Appearance



1850K

6000K 30000K

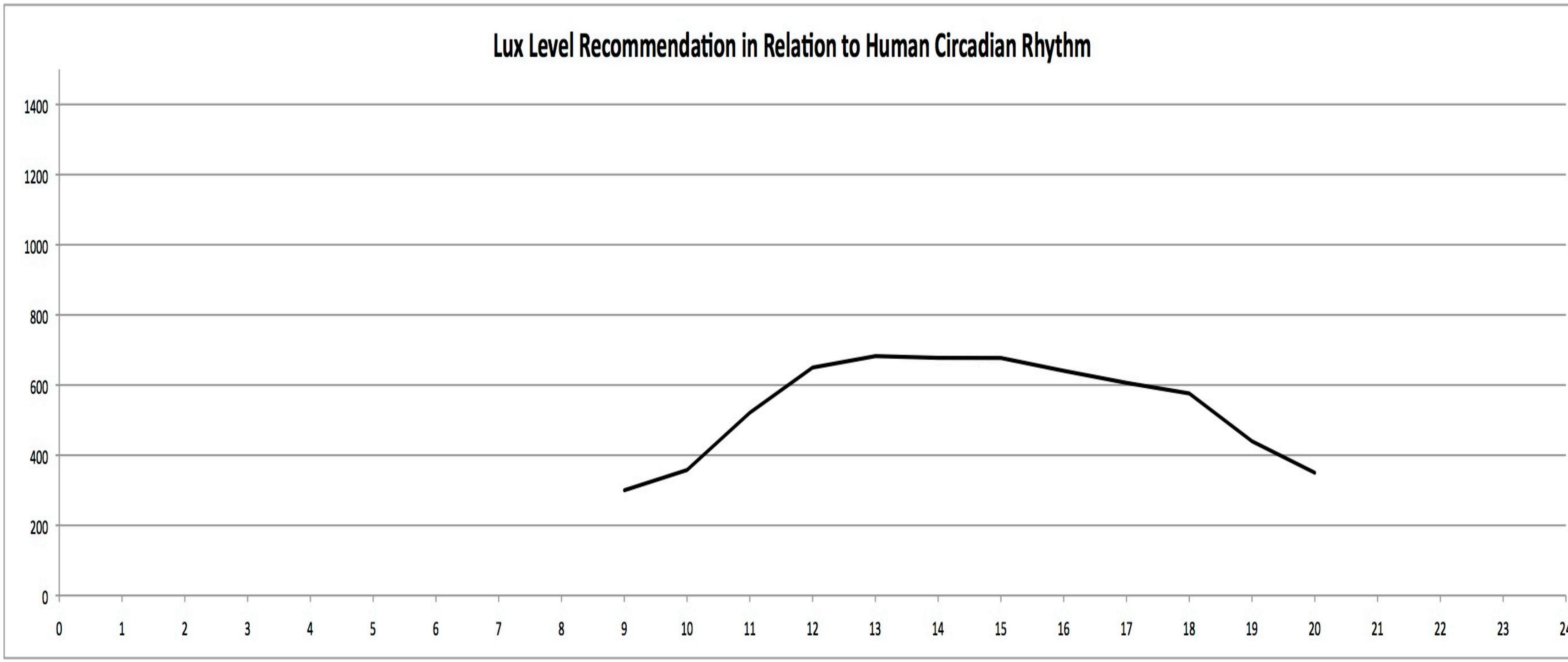
Light Level Findings



Figueiro et al 2006

"Light levels as low as 30lux at the eye for 30 minutes is the minimum threshold for melatonin suppression."

Light Level Recommendations

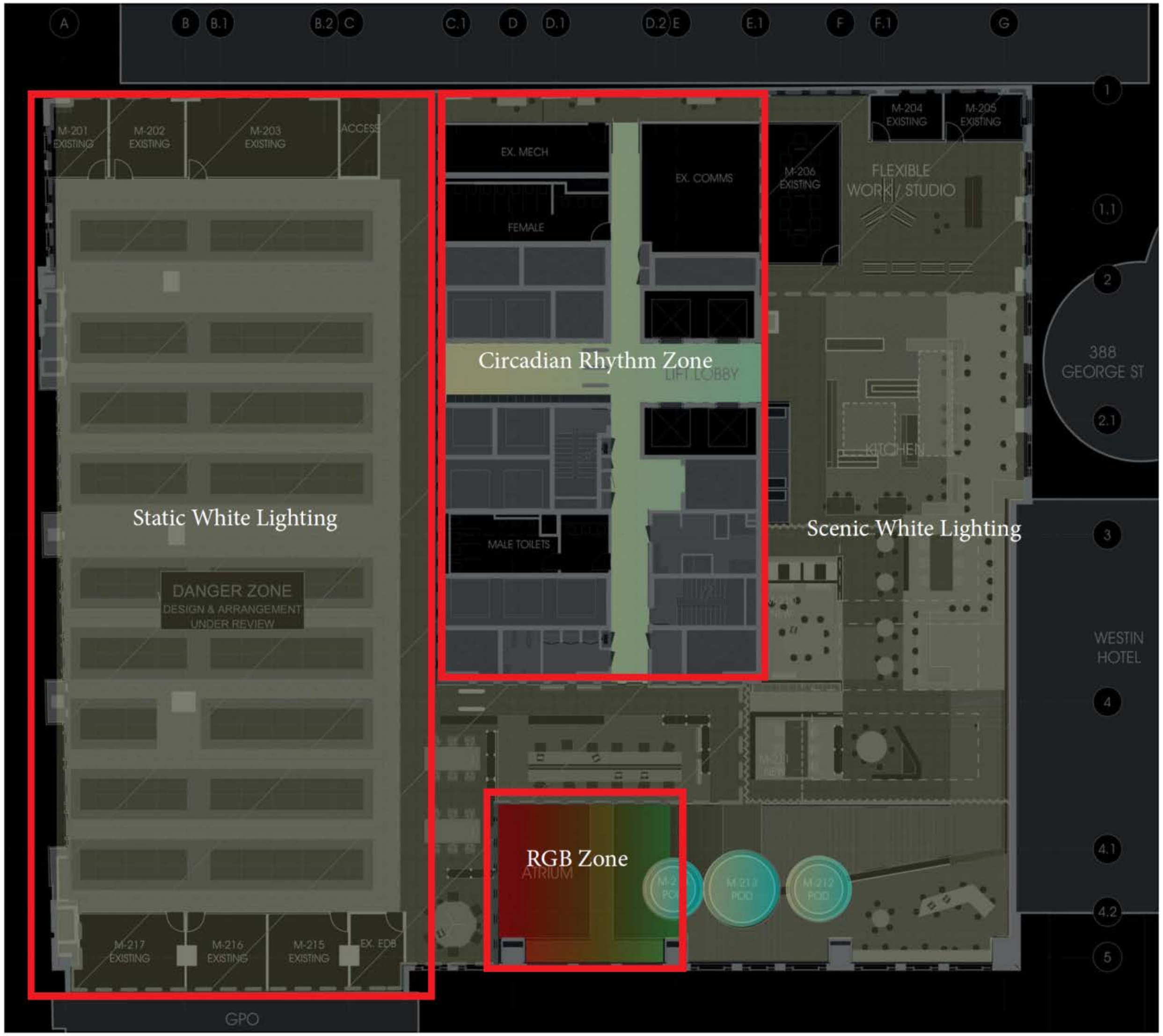


Putting this in Practice

Design Parameters

Time	Light Levels	Colour Temperature
7-9am	300lux	3000K and increase 3500K
9-11am	Gradually increase 450 lux	3500- 4500K
11-1pm	400-700 lux	Gradually rising to 5000K increasing to 5500k
1-2pm	Stay at 700 lux	Gradually rising to peak of 5500K
2-4pm	Gradually decreasing to 600 lux	Gradually decreasing to 4000K
4-6pm	Gradually decreasing to 300 lux	Gradually decreasing to 3000K

Proposed Zoning Concept

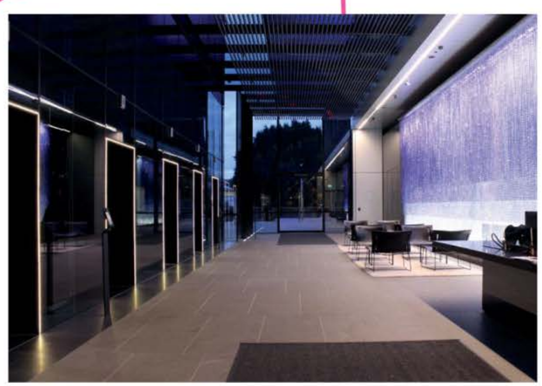


Precedence References

Static White Lighting - Arup Library

Circadian Lighting Zone - Conde Nast

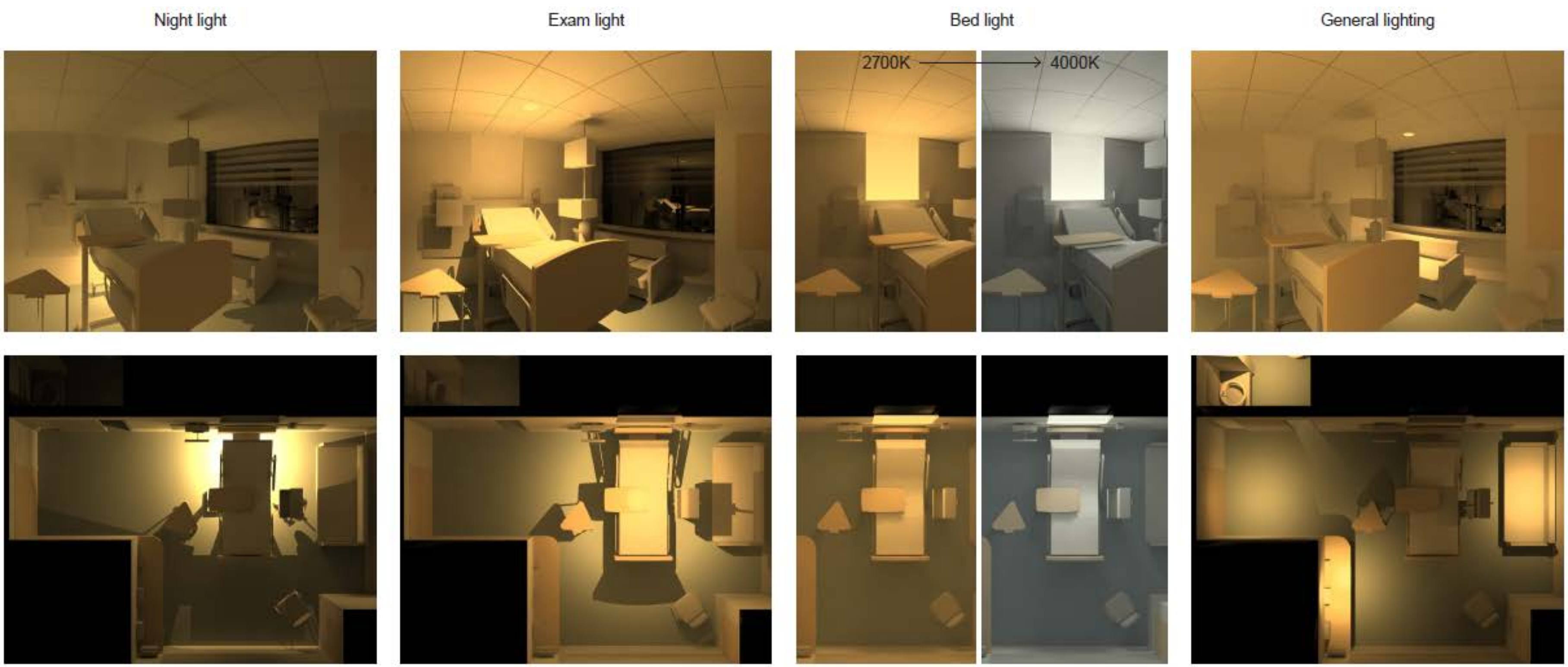
RGB Colour change - One Central Park



Scenic White Lighting - 31 Ultimo Rd

Scenic White Lighting - GPT HQ

Dynamic White Applied Projects



Dynamic White Applied Projects

Dynamic White vs. 'Tunable White'

Summary

Opportunities for lighting design

- Create more healthy visual environments/ experience

- Work in harmony with circadian rhythm
  - Modulate the spectrum and colour of light in symbiosis with the natural lighting cycle

Opportunities for lighting design

- Work in contrast with circadian rhythm
  - Create spaces where time is ‘suspended’
    - Jet lag treatment
    - Treatment of SAD syndrome
    - Increased productivity (?)
    - Night shift workers, emergency room applications

- Circadian lighting zoning
  - Different areas in a building can be treated in different ways depending on applications
  - 24 hours cities
    - Promote alertness with cooler light for on highways
    - Promote circadian entrainment in city centres/ residential streets

Challenges for lighting design

- Increasing complexity of design:
  - Design with a new ‘time’ dimension.
  - Dynamic lighting, more similar to theatrical lighting, where a ‘lighting plot’ is developed
  - Activity based lighting

- Balancing relationship between directionality, intensities and spectral content of light over time

Challenges for lighting design

- Circadian lighting and energy codes
  - Perceived as more energy demanding
  - Warm light wrongly perceived as less efficient than cool white because of photometric definitions

- Increased complexity of control systems
  - Automatic dynamic operation versus Manual/ Individual preference


Thank You!