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A White Paper from the IALD European Regulatory Affairs Working Group

Lighting Design for Health, Wellbeing and Quality of Light, A Holistic Approach to Integrative Lighting

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Lighting Design for Health, Wellbeing and Quality of Light, A Holistic Approach to Integrative Lighting

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Abstract

Designing a good lighting environment has become more complex. Until recently, lighting designers, architects, engineers, and lighting manufacturers, pretty much anyone involved in lighting design, have concentrated on creating a lighting environment for the visual functions that respond to architecture and are limited, increasingly, by requirements and regulations on sustainability and energy efficiency. This has resulted in curtailing artificial light solely to the visible part of the electromagnetic spectrum. However, research suggests that the lighting environment should also support human health and wellbeing providing the right light in the right place at the right time and involving parts of the electromagnetic spectrum that do not contribute significantly to vision.

The purpose of this paper is to try and assist in considering all different aspects of lighting that influence the health and wellbeing of the user. Although this is not a medical or scientific paper it tries to take a more holistic approach of what we are calling "*Integrative Lighting"* as is defined in CIE S 026:2018[i]

Integrative Lighting is the concept describing the connection between lighting, health and wellbeing. Lighting that focuses on people should balance visual, emotional, and biological benefits of light and provide good vision while satisfying the emotional and physiological needs of the users. The work done in the field in the last 20 years found that lighting, stimulates non-visual aspects of human psychology and physiology.

Everyone has an individual reaction to light. In general, this paper deals with an average level of reaction for the general population. However, reactions of people who do not form part of the "majority" population have different reactions. This includes the neurodiverse, the old, the very young and people who exhibit photosensitivities caused by disease or previous exposures. All need to be considered in developing lighting design. For further information see : [ii]

Lighting Design and Health

Separately from light providing visual stimulus, Light has significant effects on non-visual systems within the body. The direct effect of light refers to the immediate (can be milli-seconds) psychological and physiological response that a person experiences upon exposure to light. It includes stimulation of alertness and performance by mediating neuroendocrine. Physiological and cognitive functions.

The dampening effect on alertness and mood of too low daytime light levels can worsen the outcome of tiredness caused by sleeping problems, i.e. the direct and indirect effects of light can be cumulative. This is covered in detail in the section 'Circadian Rhythms'. Having the right light is thus critical in workplaces for example where sleep deprivation, and insufficient direct alerting / mood enhancing light combine to form the biggest problems for attention and mood: feeling sleepy, compromised working memory, less adaptability, susceptibility to mood swings / anxiety and slower reaction times / errors of judgement both of which can lead to accidents. Thus, correct light is essential where continued focus and productivity are essential.

There is growing evidence that longer wavelengths of light directly affect Mitochondria that regulate many aspects of our bodies including reducing blood glucose and increasing metabolic rate. This is covered in the section 'Mitochondrial effects of IR and Near IR'.

There is no doubt that daily exposure to natural daylight for extended periods is the best way to provide the human's natural needs for light to create wellbeing. It is not possible to provide the requirements in a fully electrically lit environment. All we can do is to make our best endeavours to improve the electrically lit environment and avoid lighting design that negatively impacts the aspects of wellbeing discussed in this paper.

The following sections review the current state of knowledge of how light affects these different systems in the body:

Circadian Rhythms

In humans and in fact most species, the daily pattern of consolidated sleep and awake state is influenced by the timing of exposure to light and darkness.

"The daily light-dark cycle governs rhythmic changes in the behaviour and/or physiology of most species. Studies have found that these changes are governed by a biological clock, which in humans is located in two brain areas called the suprachiasmatic nuclei. The circadian cycles established by this clock occur throughout nature and have a period of approximately 24 hours. In addition, these circadian cycles can be synchronised to external time signals but also can persist in the absence of such signals. Studies have found that the internal clock consists of an array of genes and the protein products they encode, which regulate various physiological processes throughout the body. Disruptions of the biological rhythms can impair the health and well-being of the organism". [iii]

Exposure to the 24-hour solar cycle normally ensures that circadian rhythms of performance and alertness peak during daytime and that a consolidated sleep is achieved at nighttime. Without regulation, the human circadian cycle runs on average 24.2 hours in a range of 23.5 to 25 hours, in a constant light environment, therefore daylight entrainment is necessary to keep us correctly synchronised with the natural world.

For all people, but especially those suffering with circadian rhythm sleep/wake disorders, artificial light can be used (with the appropriate time and intensity exposure) to readjust their sleep/wake cycle to their internal rhythms. To put it in simpler terms: daily colour and brightness variations in the environment are directly connected to the body's daily rhythmic changes.

Lighting and Circadian Rhythms

There are certain lighting aspects or qualities that affect the circadian rhythms of humans. These in brief are quantity, spectral power distribution of the light source, timing and time of exposure, spatial distribution, and light short-term history. One must understand that the human circadian system reacts differently than the human visual system. When we are normally referring to quantity of lighting levels, we are talking about the visual system needs. To entrain the circadian system, a greater amount of light with specific spectral characteristics and appropriate timing is required. The circadian system is more sensitive to shorter wavelength "blue" light while the visual system is most sensitive to the middle portion of the visible spectrum "green".

The most important aspect is that, although our visual system is not significantly dependent on the timing of light exposure, therefore responding well to light stimulus at any time of day and night, the circadian system can respond with a phase advance or delay, interfering with the synchronisation of our biological clock and a normal day / night cycle depending on timing. Also, the visual system reacts in less than a second while the circadian system responds to light only after an extended exposure. The biological clock, contrary to the visual system, does not respond to spatial patterns. The photoreceptors involved in the non-visual responses do have some spatial distribution nevertheless the axons of the cells form a network all over the retina, resulting in the possibility to react to light from different directions, with a small preference to light from above. Finally, the higher the exposure to light during the day the lower the sensitivity of the human circadian system to light at night.

Disturbance of the Biological Clock

Light is typically installed for the purpose of illuminating space to allow wellbeing, comfort, entertainment, or work. Similarly shutters, blackout blinds or curtains over windows are often used to prevent exposure to daylight and facilitate prolonged sleep. Bright light enables better vision and affects mood. Additionally, the colour temperature is typically adapted to the specific environment, which is an important feature of architectural lighting design. As we know, spectral content influences circadian rhythms rather than light source technology. As was described before, the biological clock is more sensitive to the "blue" part of the spectrum and typically, the higher the colour temperature the greater the proportion of blue in the light spectrum.

When lighting designers or engineers implement a design, the user is exposed to light which affects the circadian rhythm with immediate and medium-term effects. In general, illuminance levels and light intensity in electrically lit spaces remain well below the average intensity of daylight in most inhabited places during most of the year. In this context effects on the circadian rhythms are not so much a feature of light source technology, but of lighting and lighting design in general.

Despite the beneficial effects of light, there is strong evidence that suggests that ill-timed exposure to artificial light, resulting in circadian rhythm disruption, may also cause sleep disorders and worsen even more serious conditions. These effects are directly or indirectly due to light itself, without any specific connection to any specific lighting technology.

Daytime daylight exposure can enhance nocturnal melatonin secretion, strengthen the body clock and reduce sensitivity to late evening/nighttime light exposures. However, even a single 2.5 hr bright light exposure in the early evening is sufficient to reduce the acute sleep-disruptive effects of late evening light exposure. [iv]

The non-visual effects of IR and Near IR

Light at the IR (InfraRed) and NIR (Near InfraRed) end of the spectrum contributes little to vision so isn't considered as "useful" therefore the energy used to create it counts against the current metrics for lighting efficiency. However, the health aspects of the detriment to mitochondrial and ATP health aren't being taken into consideration and the cost to health is proving to be significantly higher in its relation to personal and planetary wellness.

Recent advancements in photobiomodulation (PBM) have shown that infrared (IR) and near-infrared (NIR) light can significantly influence mitochondrial function. Mitochondria, are essential parts within cells, primarily responsible for producing energy to drive the cell. They convert fatty acids and the breakdown of glucose to adenosine triphosphate ATP. Beyond energy production, they play a critical role in regulating cell death, signalling, and homeostasis.

The body of evidence is growing in respect to the huge benefits of the red end of the spectrum thanks to the efforts of the likes of Glen Jeffrey, Robert Fosbury (both from UCL), Scott Zimmerman and many others all of whom have published thought provoking outcomes to their extensive research.

Some of the most significant outcomes of the published research is that IR and NIR when working on mitochondrial health can improve outcomes for Dementia, diabetes, heart health, wound healing, eyesight, hair health, immune system and mental health. One of the most interesting outcomes is that IR and NIR radiation can help the body to form more mitochondria, improve collagen for joint and skin health and even slow and reduce the signs of aging both externally and internally within the body. [v]

The work on IR and NIR effects on mitochondria is particularly focussed on developing specific treatments and is showing considerable success,[vi] however researchers in the field are beginning to ask whether a higher level of IR and NIR in general lighting should be considered particularly as we have moved from light sources such as the incandescent lamp that is naturally high in IR and NIR to LED which is specifically deficient in these wavelengths.

Effects of near-infrared radiation in ambient lighting on cognitive performance, emotion, and heart rate variability by Roddick et al [vii] is the first to focus on indoor illumination with increased IR and Near IR (as opposed to transcutaneous treatment etc). Their laboratory study showed that such enhanced ambient lighting had 'beneficial effects on resting high-frequency heart rate variability (HF-HRV), HF-HRV responses to cognitive demand, and feelings of pleasure, but reduced performance on a visual search task'.

IR and NIR content of general lighting is a topic we should be aware of as it has potential to impact lighting design and technology in the future. At the time of writing (January 2025) there are no published studies to inform incorporating IR and Near IR in general lighting.

LEDs and Flicker – Temporal Light Artefacts (TLAs)

In an LED system, the electronic driver determines the extent of flickering. There is no universally adopted, approved standard or metric defining flicker. This results in many LED products in the market presenting significant flickering with few providing acceptable performance and these dependent on other lighting control elements in the system.

Frequently, flickering is not obviously visible to the naked eye, short term effects cannot be measured however it contributes to the surrounding environmental stress and can create safety hazards around moving objects and machinery through strobing effects. These include the Phantom Array effect where a light source is seen as a stream of light points as the eye scans across a scene (saccades). This can become a safety issue particularly while driving as it disturbs the ability to discern the distance of a vehicle particularly in a mirror. Currently there is work on the subject of LED vehicle lighting for this and other reasons that will likely result in regulation in the next few years.

The International Commission on Illumination (CIE) Technical Note “Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models” (006:2016) [viii] gives different definitions for the perceptual effects that modulated light can produce. The unwanted changes in the perception of the environment due to light modulation are called “temporal artefacts.” It can change the visual environment compared to natural light and previous generations of light sources. In CIE’s technical note 006:2016, “flicker” is used for direct perception of the modulation.

The definition of acceptable limits for specific applications in terms of the amount of modulation is challenging. Research and recommendations are set according to a normal person, however the neurodivergent members of the population have different thresholds and reactions to flicker and strobing effect. Migraine sufferers, Epileptics and people on the Autistic spectrum are particularly sensitive to Temporal Lighting Modulation.

In the initial (2010) Institute of Electrical and Electronics Engineers (IEEE) PAR1789.[ix] Standard, risks of seizures due to flicker at frequencies within the 3-70Hz range were presented as well as biological effects on humans due to invisible flicker at frequencies below 165Hz. However, the IEEE 1789-2015 standard "Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers" is setting a few ground rules to be followed by suppliers. In its latest report, IEEE puts forwards extremely high frequency limits.

In the EcoDesign single lighting regulation current at the time of writing (EU 2019/2020)[x] the flicker requirement is measured in PstLM. Pst is the short-term flicker severity value and LM is the measurement method defined in the standards. Additionally, there is a requirement for SVM (Stroboscopic Visibility Measure). The requirement for PstLM $\leq$1 and SVM $\leq$ 0.4 at full load represents less than 50% of a normal population being able to see see the flicker and the possibility of stroboscopic effects are significantly reduced. It is likely that these values will be changed in subsequent revisions of the regulation. It is also likely that the definitions of application of PstLM and SVM will be changed as research indicates a broader range of frequencies than currently considered may have non-visual impacts on people.

Photo Biological Safety

Light damage to the eye relates to the wavelength, intensity and duration of exposure to light. As the wavelength reduces and intensity increases light has greater effects on cells in the body. Blue and UV are at the shortest wavelength of the spectrum therefore potentially most damaging though it should be noted that the heating effects of Infrared and near infrared will tend to accelerate any chemical process or change initiated by the higher frequencies of light. These are called Actinic effects.

It should be noted that the metrics required to determine the effects of light on the eye are radiant flux measured in $W \cdot m^{-2}$. Normal photopic metrics based on the $V\lambda$ curve are not reliable for determining potential for damage by light.

There has been considerable concern over the potential of eye damage from LED sources with peak intensities at the blue end of the spectrum. There is now established advice on these matters from the International Commission on Non-Ionizing Radiation Protection (ICNIRP):

ICNIRP STATEMENT LIGHT-EMITTING DIODES (LEDS): IMPLICATIONS FOR SAFETY 2020 [xi]

ICNIRP STATEMENT ON LIGHT-EMITTING DIODES AND LASER DIODES: IMPLICATIONS FOR HAZARD ASSESSMENT 2020. [xii]

From the latter paper:
"It is concluded that all surface-emitting LEDs and IREDs will be judged safe by applying the ICNIRP ELs for incoherent radiation as well as by the recommendations of CIE TC 6-38 (Lamp Safety)[xiii] for realistic viewing conditions. This conclusion applies to any LED device which does not have optical gain."

To confirm a product is not likely to cause a risk in normal use it should comply with EN 62471 Photobiological safety of lamps and lamp systems, risk group 1 or risk group 2.[xiv]

Hazardous situations can still arise from lighting equipment. Retinal damage is dependent on the size of the image of the light source on the retina, the smaller the area for a given intensity the higher the risk of damage. Therefore, the use of magnifiers to view high intensity light sources, either a telescope looking at the sun or jeweller's loupe inspecting an LED significantly increases risk. Also, failure of a system such as the phosphor departing an LED exposing the blue chip or optical failure creating an exceptionally narrow distribution can increase risk of dangerous exposure.

Existing product developments are beginning to use UV pumped LED. As the wavelength decreases risks of inappropriate emissions become greater. Also, Laser LEDs are being used, currently in specialist applications such as projection and stage lighting. Typically, the laser emission is used to excite phosphors rather than being directly emitted so as long as they comply with ICNIRP guidelines and EN 62741 these will be safe in normal use, however the risk of retinal damage from direct laser exposure is very high.

All the foregoing applies to the normal population. There are many diseases that cause humans to be specifically sensitive to actinic light and ultraviolet, this can cause skin problems as well as eye problems. The very young, particularly under 2 years old, are extremely sensitive due to the developmental state of the lens and retina. Research is also in progress to determine if he very old are also more at risk of eye deterioration from actinic light.

Lighting Design and Wellbeing

Towards Practical Implementation of Integrative Lighting

The original version of this paper was published to clarify the knowledge and research behind what was and is sold by the industry as "Human Centric Lighting" As a marketing term this is used to describe lighting equipment with variable colour temperature or lighting control systems designed to provide temporal changes to the colour temperature of fittings so equipped. In order to implement effective lighting for non-visual impacts, consideration needs to be given to broader aspects of the lighting experience of the intended beneficiaries of the installation. At that time much of the knowledge was based on specific research carried out by Prof Brainard et al for lighting systems to provide circadian entrainment for the astronauts on the ISS who are completely divorced from a natural daylight cycle and whose exposure to the electric lighting system is completely regulated thereby maximising the impact of the lighting and providing considerable medical data on their physical and psychological condition. More recently research has been undertaken on more normal, terrestrial, applications of integrative lighting.

There have been a number of metrics proposed to measure the melanopic effect in relation to the photopic measure of the Lumen. At this point we have to use something related to the Lumen for practical purposes, however this is fundamentally flawed. Using any metrics based on a spectral distribution that does not proportionately include the areas of the spectrum that provide the effects we are trying to create distorts all measures using the fundamental unit, the Lumen. One of the most significant aspects of this is the impact on energy use of lighting measured in Lumens per Watt. As the definition of the Lumen diminishes the effect of the wavelengths, we are interested in, this measure exaggerates the energy use for integrative lighting compared with photopic lighting so by this measure any lighting with a spectral distribution divergent from the Vλ curve will be measured as less efficient. This creates challenges when efficiency targets are a fundamental requirement in lighting design.

With respect to which metrics to use for integrative lighting we consider that the standard CIE S **026:2018** CIE SYSTEM FOR METROLOGY OF OPTICAL RADIATION FOR IPRGC-INFLUENCED RESPONSES TO LIGHT [1] Is the appropriate metrics to be used going forward as it has broad international acceptance. Developed based on the action spectra of the 4 visual receptors and the iPRGC responsible for melanopsin effects, this metric creates a value for any light source that compares it to the CIE D65 spectrum for daylight. This measure for illuminance is the "Melanopic Equivalent Daylight Illuminance (MEDI) Lux"

Subsequent to this publication further work has been undertaken in the CIE Second International Workshop on Circadian and Neurophysiological Photometry, 2019 and further papers published to establish recommendations for MEDI Lux levels for wellbeing reported in CIE TN 015:2023.[xv]

• During the daytime the recommended minimum MEDI is 250 lx, using daylight if available or, where addition of electric light is required, via white light with a high melanopic daylight (D65) efficacy ratio (MEDR)

• During the evening the recommended maximum MEDI is 10 lx, starting at least three hours before bedtime. To achieve low MEDI values, using electric lighting with a low MDER is advisable.

• During the night, the recommended maximum ambient MEDI is 1 lx, and the sleep environment should be as dark as safely possible, reverting to the 10 lx maximum MEDI for unavoidable activities where more light is required for vision.

These are not absolute recommendations rather they are indicators of thresholds where melanopic effects are likely to be measurable and effective. It must also be noted that these are levels measured vertically at the eye, not the usual horizontal illuminance design targets. They are also specific to a typical 32 year old. Correction factors relating to the lower transmissiveness of the ageing eye may need to be applied for projects with an older population of users, such as care homes. CIE S 026/E:2018[1] contains graphs and information that may be helpful in determining such correction factors.

MEDR values for specific light sources and light fittings can be obtained from manufacturers. Failing this a spectral power distribution can be obtained from the manufacturer or by measurement with a photospectrometer and these values can be entered in the CIE S 026 Toolbox < https://bit.ly/2T9QLTL> that will output MEDI and MEDR values for design calculations.

Currently there is ongoing research determining the effectiveness of these values practically in the office environment with specific dedicated luminaires. This is summarised in Sexton & Raynham "Feelgood Factors" in June 2024 Lighting Journal. This shows indicatively positive outcomes using the 250MEDI Lux delivered by a specific fitting in a workplace environment.

Requirements and Regulation

At the time of writing there is ongoing consideration of incorporating requirements for integrative lighting in buildings. Specific requirements are set out in the WELL Building Standard, currently edition 2. This is a voluntary standard intended to recognise human comfort and wellness considerations in new build and refurbishment projects. Originating in the USA it is used internationally, and aspects of these recommendations are being added to various national building standards.

The lighting section < https://v2.wellcertified.com/en/wellv2/light> includes subsection L03 on Circadian Lighting and sets the following requirements:

For workstations used during the daytime, electric lighting is used to achieve the following thresholds:

a. The following light levels are achieved for at least four hours (beginning by noon at the latest) at a height of 45 cm above the work-plane for all workstations in regularly occupied spaces:

Tier	Threshold		Threshold for Projects with Enhanced Daylight	Points
1	At least 150 EML [136 melanopic EDI]	OR	At least 120 EML [109 melanopic EDI] and either L05 Part 1 or L06 Part 1	1
2	At least 275 EML [250 melanopic EDI	OR	At least 180 EML [163 melanopic EDI] and either L05 Part 1 or L06 Part 1	3

b. The light levels are achieved on the vertical plane at eye level to simulate the light entering the eye of the occupant.

These relate to separate requirements for accessibility to daylight set out in section L01 of the standard.

In section L04 Electric Lighting Glare Control the requirement is to meet UGR 19 for fittings, the area or for 100% of light to be emitted above the horizontal plane or a calculation of the space providing a glare rating of UGR19 or better. It would appear to be unlikely to meet requirements for both L03 Tier 2 and L04. As a scoring standard it is possible to achieve a score sufficient for even a Gold award without meeting any of the lighting requirements, In practice it is often found that cheaper means of meeting requirements for other building factors will result in the points for lighting being deprecated. This is unfortunate as the WELL system does allow for exceptional situations and applications so rather than abandon the argument for effective solutions, make a case for the assessor to elevate the decision to WELL HQ.

DIN/TS 67600:2021 Complementary criteria for lighting design and lighting application with regard to non-visual effects of light[xvi]

This standard describes the requirements of melanopic effective lighting in the terms of CIE S 026:2018 described above and proceeds to identify, in detail, aspects of design considerations that will affect the implementation of a successful integrative lighting scheme. It details the design processes and procedures that are necessary to effectively incorporate integrative lighting. It concludes with a section on operation and maintenance that merits quoting:

"The visual, emotional and non-visual effects of the light are taken into account during planning, which must then be ensured during installation and operation. The needs of the users must be taken into account during planning and should be met during operation.

The way the lighting system works and the lighting pattern, as well as the way the system works, should be understandable and comprehensible for the user. New users must be informed about how the lighting system works and the lighting pattern explained. Providing easy-to-understand instructions is helpful.

This can be anchored in the induction plan for employees, for example. Knowledge of how the lighting system works, the programming and the lighting pattern enables the building technician to make adjustments if necessary. This can be necessary, for example, due to a change in use or a change in personnel. It is particularly important to regularly check the lighting system to ensure it is functioning as intended and to document the results in a maintenance plan. This applies to the lighting intensity of the individual light colours, possible deviations from the planned light colours as well as the timing (control) and the set lighting scenes. The user is sometimes unable to immediately recognise errors in the function. Therefore, the lighting, and especially the lighting control, must be regularly maintained. After maintenance, for example, it is necessary to check whether lamps with the wrong light colour have been installed in the system. NOTE After commissioning and after about one year, feedback on the benefit satisfaction should be obtained from the user. Under certain circumstances, the lighting pattern or the timing must be readjusted to suit user requirements, or the functionality of the lighting system must be discussed again.

A maintenance plan for the non-visually effective lighting system must be drawn up - see DIN EN 12464-1 or DGUV-1215-210 (54).

The measurement is carried out in accordance with the specifications of DIN/TS 5031-100:2021-09."

This is generally good practice for all lighting design but even more important in respect of integrative lighting.

Lighting Design and Quality of Light

The Quality of Light is very largely a subjective, experiential matter. It is also completely influenced by context. There have been many attempts to create a metric for lighting quality however none have managed to encompass all the many variables, not only of measurable parameters, but of different people's varied visual experience. It is clear that light levels alone do not indicate quality; however, this measure can be important for specific task lighting where visual acuity is required. Similarly, colour fidelity metrics can be important both for some specific tasks and for general lit experience. Glare metrics are also important in certain task situations however the quality of lighting sparkle (Richard Kelly's "Play of Brilliants") adds a specific quality to many lit environments.

Clearly lighting quality must include aspects of health and wellbeing that we are identifying in this paper, appropriate lighting levels, and colour fidelity to achieve the visual tasks in the space being designed for, however it must be understood that aiming for higher levels of the measurable factors certainly does not result in high lighting quality. One consideration to bear in mind is that humans have evolved with natural light over many millennia. This includes daylight at high levels during daytime and firelight at night. We have only had significant levels of man-made light for around 200 years; therefore we react to the stimuli of natural light and where we aim to provide man made light we need to be aware of our reactions to this compared to natural light. Exposure to natural views and daylight has been shown to enhance psychological well-being, reduce stress, and improve overall mood and alertness, which underscores the importance of integrating these elements into lighting design. Variability and rhythm in lighting, mimicking natural patterns, can also support circadian rhythms and improve sleep quality.[xvii]

In addition to these considerations, it is important to notice that alongside the circadian effects of light exposure effects are also influenced by lighting quality. This is especially defined in terms of directionality and dynamism. The directionality of light, which encompasses the flow and strength of light from specific directions, helps in distinguishing details of tasks, surface textures, and three-dimensional objects. This aspect significantly influences communication, the appearance of spaces, and the overall appreciation of an environment. Furthermore, the direction of light is a quick reference to the variability of natural light and the rhythm of light changing over time, contributing to visual performance, arousal levels and the pleasantness of the environment, as well as a zeitgeber of circadian functions. The incorporation of dynamic lighting, which can be achieved through both natural and artificial means, can enhance the visual and emotional experience within a space.

A full consideration of all these factors, the particular design of the space and how users feel are all factors that need to be considered in designing for high lighting quality.

The definition of Quality of Light is as vague and as subjective as the number of lighting designers in the world. Many believe you cannot really define light quality. Even more some would argue that the emotional benefits of a good lighting design for health and wellbeing cannot be quantified. And although this to some extent is true, when it comes to light and health there are ground rules. It would be useful to have standards and guidelines integrated in legislation to be used as a tool for even better design.

Colour Quality Metrics

As lighting designers, one of the important metrics we consider in our quest to design lighting quality is colour. Historically, the Colour Rendering Index was created in the late 1940s to compare the colour rendering of fluorescent lighting with daylight and incandescent light. CRI in its definition is "a measure of a light source's ability to show object colours 'realistically' or 'naturally' compared to a familiar reference source, either incandescent light or daylight." However, a light source with a higher CRI does not necessarily guarantee a better Quality of Light.

The IES Method for Evaluating Light Source Colour Rendition (IES TM-30-15)[xviii] was developed to address limitations of the CRI metric. It proposes a new metric concept with two metrics: a Fidelity and a Gamut index. In addition, a Colour Vector Graphic is provided for better understanding. It also uses 100 comparative colours compared to the 16 or even 8 used to define CRI significantly reducing the opportunity to "game" the CRI measurement by addressing only the colours in the test samples rather than the entire spectrum.

Although TM-30-15[24] is a significant improvement, with the Colour Vector Graphic in its simplicity being useful in understanding the properties of a light source, it has not displaced CRI as the predominant colour metric. Typically, the colour fidelity scores of TM30 remain close to CRI scores for the majority of light sources, usually slightly lower. Since the 2015 version of TM-30 there have been two revisions, current version is TM30-20-E2. It has been established that there are other factors at play in considering the experience of colour rendering. To account for this a weighting system has been added to cover Preference, Vividness and Fidelity. This increases the complexity of using colour metrics in lighting and indicates the difficulty of rendering human perception in metrics.

Conclusions

Since the first edition of this paper, research has moved on as has the practice of designing for Wellbeing. There are now several projects where the design has been led by the principles discussed, some of them very successful, particularly in the Care Home sector where circadian entrainment and improved sleep through avoiding disruption to melatonin secretion make significant improvements to the safety and happiness of residents. We are still learning how to apply this knowledge more widely in lighting design.

As a profession Lighting Designers need to approach this topic with knowledge and with care. We need to be fully informed and communicate clearly the benefits and risks of specific lighting interventions to health and wellbeing. Our primary goal is minimising any potential harm to people in the environments we design. We need to understand the population we are specifically designing for and be aware that there are different requirements for different groups including the very young, the old, those with visual impairments and those who are neurologically diverse.

The original paper was written to clarify the state of research among a market that was being flooded with products labelled "Human Centric Lighting" and claiming to offer "benefits" that were not defined or proved until some of the more recent papers now listed in this revised paper. Research is forever taking us forward and new areas appear. In this paper we have included current work on the near infra-red impacts on Mitochondria. This has the potential for further impacts on designing for wellbeing in the not-too-distant future.

Finally, much of what we have discussed is no more than mitigation of the reality that we spend most of our lives in electrically lit environments rather than under natural light out of doors. We can make improvements to the electrically lit environment, and we can advocate for better access to daylight indoors and more opportunity to spend time out of doors in nature. We cannot duplicate or replace natural light and should not pretend that we should or can.

So, after all these developments in lighting and health sector and the ongoing revelations, does that mean that the lighting designer has to have a medical degree in order to design? The key word is responsibility. As lighting design professionals, we always should research and work with the user in the centre of our design. We need to see this new framework and possible standards to be introduced as an opportunity and not a threat to our artistic vision and professional progress. On that note, we have and should have a key role and a saying on where things should be going in terms of research, the lighting industry, and lighting design of the future.

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