

LED

professional

Review

LpR 116

July/Aug 2026

HUMAN CENTRIC LIGHTING

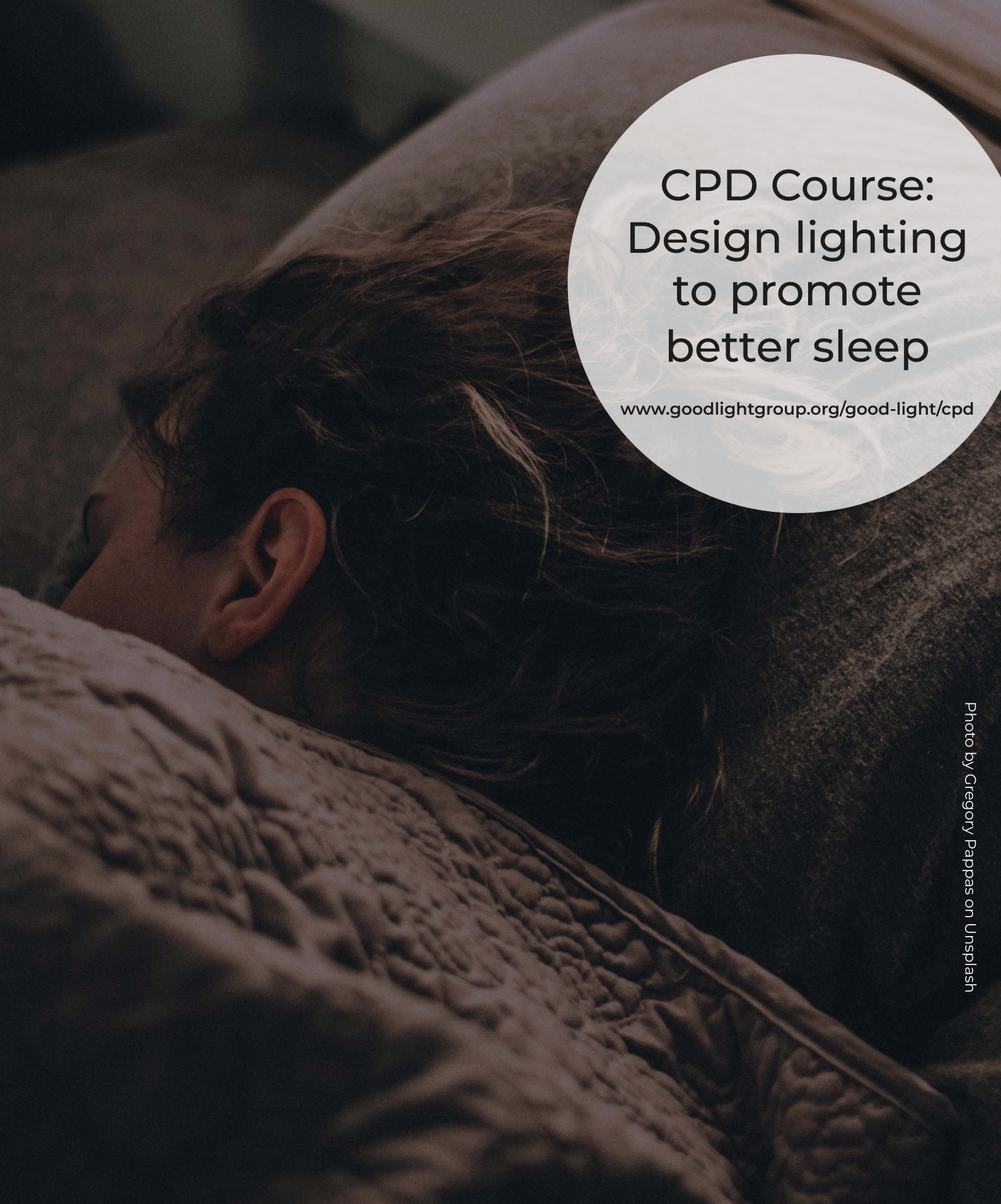
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CPD Course: Design lighting to promote better sleep

www.goodlightgroup.org/good-light/cpd

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Sleep is fundamental to our health, performance, and wellbeing — yet it is increasingly disrupted by our everyday's actions and the way we design and light our buildings. This CIBSE-approved CPD course explores the science of sleep, our internal body clock, and how integrative lighting design can actively support healthier sleep–wake rhythms.

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HUMAN CENTRIC LIGHTING



Human Centric Lighting has evolved from an emerging research topic into one of the most exciting and challenging fields in professional lighting. While many fundamental questions have been answered, even more opportunities are opening up as science, technology, lighting design and building intelligence begin to converge.

With this special issue, LEDprofessional Review brings together an exceptional group of international experts from science, industry and practice. Their contributions demonstrate that Integrative Lighting is no longer about individual products or isolated metrics. It is about creating lighting systems that better support people while remaining practical, measurable and economically viable.

Among the highlights are Jan Denneman's vision of Good Light as the industry's next growth opportunity, Lawrence Lin's concept of HCL-ready systems, Signify's fascinating perspective on UVB and vitamin D, Oliver Stefani's controlled laboratory research on dynamic lighting and sleep, Mariana Figueiro's latest work on light and Alzheimer's disease, as well as practical solutions and technologies presented by Lumitech, Nichia, ams OSRAM, Regiolux, Zumtobel and TRILUX.

The discussions around Human Centric Lighting are far from over. Questions remain about standards, implementation, cost-effectiveness and the balance between scientific evidence and commercial claims. We hope this issue contributes meaningful insights and stimulates further dialogue across our industry.

We believe LpR #116 will inspire new ideas, new discussions and, above all, better lighting. Enjoy your read!

Yours Sincerely,

Siegfried Luger

Founder & CEO of Luger Research e.U.
Publisher of LEDprofessional

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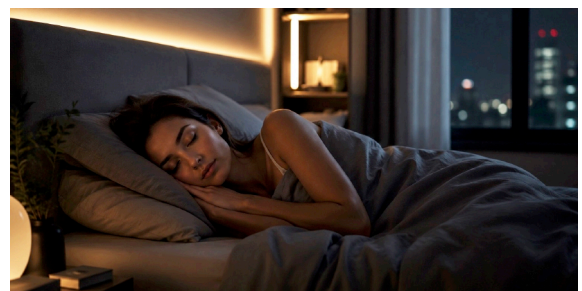
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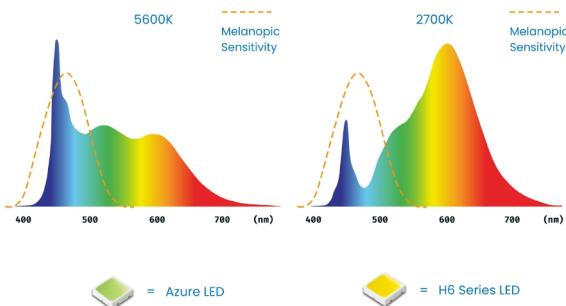
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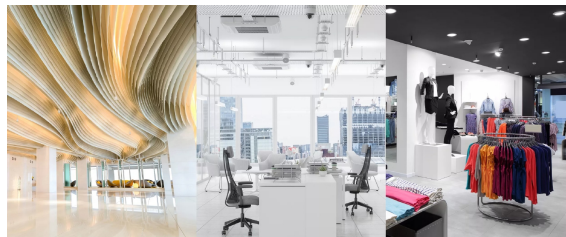
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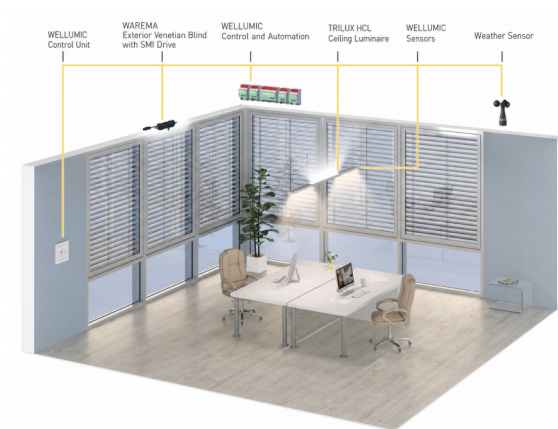
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Jan Denneman

Jan Denneman is a physicist, lighting expert and international speaker. He has more than 45 years of international experience in the lighting industry. He held senior leadership positions at Philips Lighting (now Signify) and served as Chairman of both the Global Lighting Association and LightingEurope.

He is the founder and Chairman of the Good Light Group, an independent international non-profit organization that promotes healthy indoor lighting through science, education and collaboration.

His work focuses on increasing awareness of the effects of light on the circadian system and its impact on sleep, daytime alertness, mood, health and wellbeing. Through the Good Light Group, publications and international speaking engagements, he translates scientific knowledge into practical guidance for people and organizations.

His mission is to change the way we think about light and make the right light at the right time a natural part of a healthy lifestyle.

Good Light: The Next Growth Story for Our Lighting Industry

For more than a century, our industry has continuously reinvented itself.

We moved from incandescent lamps to more efficient lighting technologies. We embraced LEDs and substantially reduced energy consumption. We introduced digital controls, connectivity and intelligent lighting systems. Each of these innovations created new markets, new business opportunities and, most importantly, better lighting.

Today, I believe we are at the beginning of another transformation. Human Centric Lighting, Integrative Lighting, or simply good light, has the potential to become the next growth story for our industry.

This special issue of *LED professional Review* demonstrates how far the field has progressed. What began as an emerging area of scientific research has developed into a rapidly expanding body of evidence on the effects of light on sleep, alertness, wellbeing and human performance.

Light remains one of the most overlooked elements of healthy buildings. Yet poor sleep has become one of the greatest public health challenges of our time, and improving the quality of indoor lighting during the day and evening remains a largely untapped opportunity.

The timing could hardly be better.

The lighting industry can be proud of what it has achieved. LED technology has reduced lighting energy consumption to a fraction of what it was two decades ago. But as products become increasingly efficient and commoditized, energy savings alone are no longer enough to drive future growth. Our industry needs a broader value proposition.

That opportunity lies not in the electricity bill, but in the people inside the building.

Buildings exist to serve people. Offices support productive work. Schools support learning. Hospitals support recovery. Homes support comfort and wellbeing. In every one of these environments, people represent by far the greatest value. If lighting can contribute, even modestly, to better sleep, greater alertness, improved mood or enhanced performance, its value

far exceeds the cost of the energy it consumes.

For many years, we have primarily explained the value of lighting in terms of visibility, aesthetics and energy efficiency.

Those remain essential. Good light builds upon them rather than replacing them. Good light must first allow us to see comfortably, create attractive spaces and use energy responsibly. It adds another dimension: supporting the people who spend almost 90 per cent of their lives indoors.

Good light should not be reduced to a single metric or technology. It is not simply about melanopic quantities or dynamic lighting systems. It is about designing indoor environments that work in harmony with human biology. Daylight, electric lighting, architecture, controls and user behavior all contribute to that objective. Ultimately, good light is about creating indoor environments that support health, wellbeing and human performance.

For all these reasons, I am optimistic about the future of our industry.

Our scientific understanding continues to evolve, and we should always distinguish between established evidence and promising new research. Independent dialogue between scientists, lighting professionals and industry will remain essential to translate new knowledge into lighting solutions that create real value for people.

Good light offers the opportunity to redefine the role of lighting: from infrastructure that helps us see to an environmental factor that actively supports health, wellbeing and human performance.

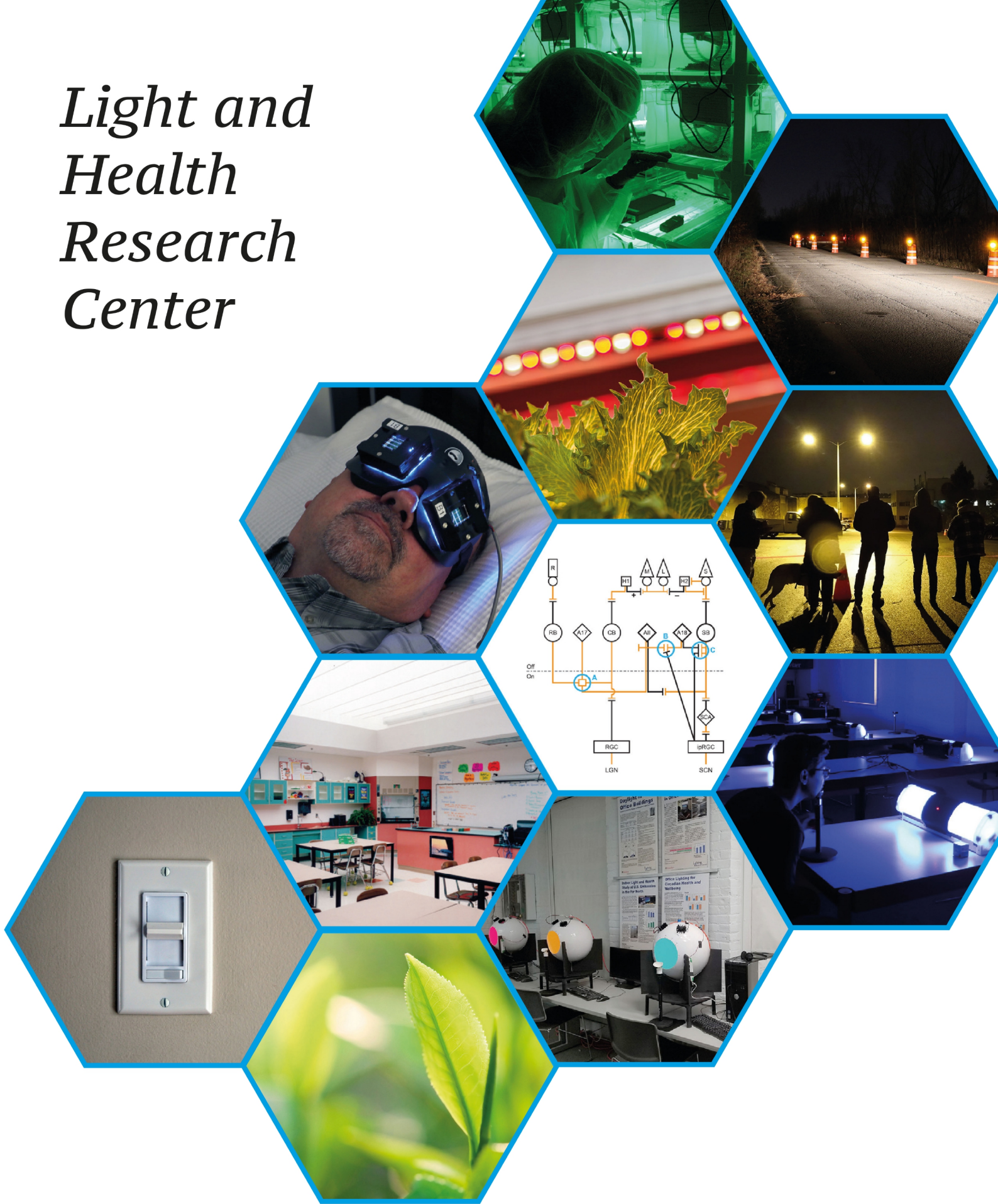
It opens the door to a new generation of lighting solutions, products and services.

By creating greater value for people, good light benefits society and provides new opportunities for our industry while laying the foundation for sustainable and profitable growth.

I hope the articles in this special issue will stimulate further dialogue, innovation and collaboration as we shape that future together. ■

J.D.

Light and Health Research Center



Advancing the health of people and the planet through the science of light.

Designing Lighting to Promote Better Sleep: A New Good Light Group CPD Course

Lighting has traditionally been designed to support vision. However, research over the past two decades has shown that light also regulates the human biological clock, influencing sleep, alertness, mood, and overall well-being. This growing understanding is changing how lighting professionals approach the built environment.



To bridge the gap between research and practice, the Good Light Group Foundation has developed the Continuing Professional Development (CPD) course Designing Lighting to Promote Better Sleep. Recently approved by CIBSE, the course is available free of charge for lighting professionals, architects, engineers, and others involved in indoor environment design.

The course introduces the science of sleep, explaining sleep stages, circadian rhythms, and the role of daylight in synchronizing the body's internal clock. It also examines how insufficient daytime light and excessive evening light can disrupt circadian rhythms and reduce sleep quality.

A central topic is melanopic Equivalent Daylight Illuminance (m-EDI), the metric used to assess the biological effectiveness of light. Participants learn how m-EDI can help evaluate whether lighting supports healthy circadian entrainment while minimizing unnecessary evening light exposure. Current recommendations are translated into practical lighting design guidance.

The course also presents the principles of Integrative Lighting Design, demonstrating how visual comfort, circadian health, and energy efficiency can be addressed within a single lighting concept through practical project examples.

The CPD is presented by three members of the Good Light Group. Dr. Virginie Gabel explains the science of sleep and circadian rhythms, Roger Sexton explores the visual and non-visual effects of light, and Kevan Shaw demonstrates the practical implementation of these principles through an Integrative Lighting Design case study developed with James Sherman of Foster + Partners.

Developed as part of the Foundation's mission to improve awareness of the relationship between light, health, and well-being, the course translates scientific evidence into practical guidance without promoting specific products or technologies. Participants who successfully complete the assessment receive a CPD certificate. The course is available free of charge through the Good Light Group website, making evidence-based knowledge widely accessible to the lighting community. ■

CIE Launches Two Advanced Tutorials on Measurement Uncertainty and LED Reference Spectra

led-professional.com/all/cie

The International Commission on Illumination (CIE) has announced two specialized tutorials taking place in September and November 2026, offering lighting professionals, metrology experts, and researchers an opportunity to deepen their knowledge of modern photometric and radiometric measurement techniques.



Both tutorials are organized by CIE Division 2 – Physical Measurement of Light and Radiation and focus on internationally recognized CIE methodologies and publications. ■

A Comprehensive Checklist for Reporting Light Characteristics in Laboratory-based Human Studies Using Light as an Intervention

<https://cie.co.at/publications/comprehensive-checklist>

The CIE, through initiatives like the publication of CIE S 026/E:2018 "System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light", played a key role in establishing standards for measuring how different aspects of light affect our eyes. This includes defining specific functions, quantities and metrics to describe how optical radiation

stimulates various photoreceptor types, which can influence non-visual effects of light on the human retina through melanopsin-expressing intrinsically photosensitive retinal ganglion cells (ipRGCs). To date, however, there is a lack of consensus within the large community studying the ipRGC-influenced effects of light on humans (i.e. circadian entrainment, pupillary light reflex, etc.) in laboratory-based studies about which characteristics of light to report. As a result, the lack of suitable reporting practices hinders direct comparisons between studies and makes it difficult to draw robust conclusions about the effects of light exposure on human health and well-being.



July 2026

New CIE Technical Note CIE TN 016:2026

A comprehensive checklist for reporting light characteristics in laboratory-based human studies using light as an intervention

This Technical Note provides the first internationally endorsed consensus checklist (ENLIGHT), established through a modified Delphi consensus process, for reporting light interventions in laboratory-based human studies, helping to standardize how light exposure is measured and reported to improve reproducibility and comparability across studies. The Technical Note is expected to improve the quality and transparency of light research, facilitate meta-analyses, accelerate the development of evidence-based lighting and light-therapy solutions, and support better translation of research into clinical practice, public health and lighting design. The document is written in English. It consists of 9 pages and is freely downloadable from the CIE website. ■

Bright Days, Dark Nights: Translating Science on the Non-visual Effects of Light into Public Health Guidance

led-professional.com/all/bright-days-dark-nights

Clear, proportionate guidance on light and darkness can help people and institutions structure daily environments to support circadian alignment, sleep, alertness, mental health, and wellbeing.

Background: Light is a daily environmental exposure that can influence circadian timing, sleep, alertness, mood, and cognition, yet public health guidance still focuses mainly on optical-radiation hazards rather than healthy patterns of visible light and darkness.



Conclusion: Clear, proportionate guidance on light and darkness can help people and institutions structure daily environments to support circadian alignment, sleep, alertness, mental health, and wellbeing. ■

Illuminating Engineering Society and National Lighting Bureau Sign Memorandum of Understanding to Advance Lighting Excellence

led-professional.com/all/illuminating-engineering-society

The Illuminating Engineering Society (IES) and the National Lighting Bureau (NLB) have signed a Memorandum of Understanding (MoU) establishing a strategic partnership to advance collaboration in lighting education, public outreach, and industry engagement.



IES & NLB Announce Joint Memorandum of Understanding

New York, NY USA, 29 June 2026

The Illuminating Engineering Society (IES) and the National Lighting Bureau (NLB) are pleased to announce a memorandum of understanding enabling future collaboration to improve the quality of our lighted environments.

IES and NLB have agreed to collaborate to enhance the performance, quality, and sustainability needs of our buildings to improve the

The agreement reflects a shared commitment to improving the quality, performance, and sustainability of the built environment through enhanced cooperation between two of the lighting industry's leading organizations. By combining their respective expertise and resources, IES and NLB aim to strengthen professional education, increase public awareness of the value of quality lighting, and support initiatives that benefit communities and the lighting profession alike. ■

Philips Skylight, Designed to Bring the Feeling of Daylight Indoors

philips.com/skylight

Signify announced Philips Skylight, a new ceiling lighting range designed to recreate the feeling of daylight indoors. Inspired by the natural brightness, depth and rhythm of sunlight, Philips Skylight combines advanced LED lighting technologies with intuitive everyday experiences to help people feel more connected to natural light — even while indoors.



As people spend an increasing amount of time indoors, access to natural daylight has become more limited. New Signify research found that 58% feel they spend too much time indoors, while 89% say they feel more energetic when they get enough daylight. In addition, 43% are open to solutions that recreate daylight indoors. Philips Skylight was developed to address this shift, helping people bring the feeling of daylight into their homes.

The integrated auto day rhythm feature automatically adjusts brightness and tone throughout the day. Supported by Philips BioUp LEDs, Skylight delivers brighter, blue-enriched light during the day and warmer light in the evening, inspired by research on circadian stimulation and alertness. Users can select from five preset daylight-inspired scenes depending on their activities, ranging from focused daytime lighting to warmer evening ambience. ■

Realistic Biophilic Sky Luminaire Serves Multiple Lighting Functions

led-professional.com/all/realistic-biophilic-sky-luminaire

Nightingale®, a patient-centered, design-forward lighting brand for healthcare environments, has unveiled its latest product. The Observe™ cloud luminaire has now been adapted to meet the unique requirements of MRI spaces.



Observe was designed with patients and caregivers in mind but is now also compatible with MRI suite requirements. The luminaire's advanced LED-level imagery creates a realistic, calming sky visual to help patients feel at ease during MRI procedures. At the same time, it provides caregivers with enough ambient light for observation. And when more light is required for post-scan activities such as cleanup, Observe transitions to a uniform white light that supports clarity. ■

Ledvance Wins German Innovation Award 2026 For AI-driven Lighting Robot Elix

led-professional.com/all/ledvance

Ledvance has been named the winner in the Excellence in Business-to-Consumer Lighting category at the German Innovation Awards 2026, held in Berlin in May. Following the successful debut of Elix at Lichtwoche Sauerland and its showcase at the world's leading lighting trade fair, Light + Building 2026, the award reinforces the company's reputation for driving innovation in lighting technology.



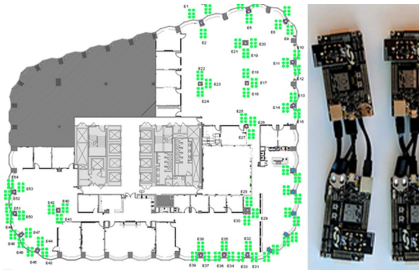
At the heart of the project is Elix, an intelligent lighting robot that seamlessly combines lighting, robotics and emotional interaction. Developed around the belief that lighting is about far more than illumination, Elix responds in real time to users' activities, moods and gestures, creating an adaptive, intuitive and lifelike experience. ■

Silicon Labs Advances Large-Scale Matter Deployments with 200-Node Matter-over-Thread Validation Network

led-professional.com/all/silicon-labs

Silicon Labs announced the successful deployment and operation of a 200-node Matter-over-Thread validation network, demonstrating the scalability, reliability and performance of Matter for large-scale smart

building, commercial IoT and next-generation smart home applications.



Announced at the Connectivity Standards Alliance's (CSA) inaugural Unify event, this highlights a key evolution in the Matter ecosystem: the industry is moving beyond proving interoperability and toward demonstrating scalability for real-world deployments. Silicon Labs' 200-node Matter-over-Thread validation network provides evidence that Matter can support the larger, more complex environments expected in commercial buildings, multi-dwelling units and next-generation smart home installations. ■

Smart Sensing, Smarter Spaces: Sunricher's Bluetooth® Mesh PIR Sensor and Nordic's nRF54L15 SoC

led-professional.com/all/smart-sensing

Sunricher built a commercial Bluetooth Mesh occupancy sensor around Nordic's ultra-low-power Bluetooth LE SoC, the nRF54L15, to bring wireless control to legacy 0–10V commercial lighting.



With Nordic's nRF54L15 SoC, Sunricher's Bluetooth Mesh PIR sensor delivers occupancy-driven, energy-saving lighting over existing 0–10V systems. This reduces wasted light, improves comfort, and eases code compliance. As a forward-looking 0–10V dimming PIR sensor Bluetooth solution, it anchors Bluetooth LE Mesh occupancy detection today and paves the way for indoor positioning and LE Audio tomorrow. The result is a scalable Bluetooth Mesh PIR sensor family that advances Bluetooth Mesh control for smart lighting across commercial environments. ■

Infinion Introduces the AIROC™ UWB TSL100 for Precise Positioning and Smart Presence Detection on a Single Chip

Infinion introduced the AIROC™ UWB TSL100, the company's first-generation ultra-wideband (UWB) product family for precise positioning and smart presence detection. As part of Infineon's AIROC portfolio, the TSL100 features a new architecture aimed at reducing power consumption and enhancing security. The product family marks the start of a scalable UWB platform intended to support future standards such as IEEE 802.15.4ab and is compliant with industry consortium standards such as CCC, Alio, and FiRa.



The TSL100 combines ranging and sensing capabilities in a single device, enabling applications such as secured vehicle access, in-cabin presence detection, access control, contactless payment, ticketing, and indoor navigation, as well as industrial use cases including asset tracking and collision avoidance. With the introduction of the AIROC™ UWB TSL100, Infineon strengthens its position in secured connected systems and expands its AIROC™ wireless portfolio with a new family of UWB devices. These devices combine precise positioning and smart presence detection on a single chip, addressing growing demand across automotive, consumer, and industrial markets. ■

Connectivity Standards Alliance Kicks Off Unify, Where the IoT Industry Decides What Comes Next

led-professional.com/all/connectivity-standards

The Connectivity Standards Alliance (Alliance) officially welcomed attendees to Unify, its premier public event created to accelerate the adoption of open standards across the Internet of Things (IoT). Taking place in Austin, Texas, Unify brings together the companies, innovators, and Alliance Members from

around the world to explore the future of secure, interoperable connectivity.



As Alliance technologies continue to define the future of open standards and connected experiences, Unify puts them to work, accelerating the next era of the IoT across homes, buildings, energy, and emerging smart environments. At a time of rapid transformation, the event creates a dedicated space to combine the technologies, partnerships, and shared vision shaping the future in connected living. ■

DLC Released Updated Networked Lighting Controls Technical Requirements

led-professional.com/all/dlc

Reinforcing the role of lighting controls as the foundation for deeper energy savings through connected commercial lighting, the DesignLights Consortium (DLC) finalized updates to its Networked Lighting Controls (NLC) Technical Requirements.



NLC systems that apply for and meet the requirements are listed on the NLC Qualified Products List (NLC QPL), which is used by industry stakeholders to select and verify high-quality NLC systems. The NLC QPL is the only list of its kind that provides extensive, verified information on interoperability, cybersecurity, and data access for each system. ■

LUCL and TALQ Join Forces to Advance Sustainable, Interoperable Urban Lighting

led-professional.com/all/luci-and-talq

The TALQ Consortium, a global standardization body enabling interoperability in smart cities, and the LUCI Association, the international network of cities on urban lighting, announced their collaboration to support cities on their path towards more sustainable and interoperable street lighting.



From July 2026, the TALQ Consortium has become an Associated Member of LUCI, while LUCI has joined the TALQ Partner Program. This two-way collaboration brings together LUCI's global community of cities and stakeholders with TALQ's technical expertise gained by developing the open, vendor-independent Smart City Protocol for managing interactive outdoor lighting and other smart city applications. ■

Zhaga Consortium Publishes Updated Editions of Books 15 and 19 for Outdoor LED Modules

led-professional.com/zhaga-consortium

The Zhaga Consortium has published updated editions of two of its specifications for outdoor LED lighting: Book 15 Edition 1.3 and Book 19 Edition 1.4. Both updated editions have been available to Regular and Associate Members since 13 July 2026.



Zhaga Books are interface specifications that define the mechanical and electrical interfaces between LED components, enabling products from different manufacturers to work together. Books 15 and 19 both address rectangular LED modules used in outdoor applications such as roadway, pathway, and outdoor-area lighting, where robust performance, optical precision, and long-term serviceability are essential. ■

A Simplified Framework and Better Enforcement for Energy Labelled Products

led-professional.com/all/a-simplified-framework

The European Commission has published its 12th Omnibus proposal on Energy and Tire Labelling.



The proposal aims to reduce administrative burdens for suppliers and retailers while ensuring that consumers continue to receive clear and reliable product information when making purchasing decisions. By preserving an effective labelling framework, the Commission seeks to support the development and uptake of more energy-efficient products, helping businesses and households reduce energy consumption, operating costs and energy bills. ■

The Digital Product Passport Registry is Now Live

led-professional.com/all/the-digital-product-passport

The European Commission launches the Digital Product Passport Registry together with a testing environment, marking an important milestone in making the Digital Product Passport (DPP) a practical reality for businesses placing products on the EU market.



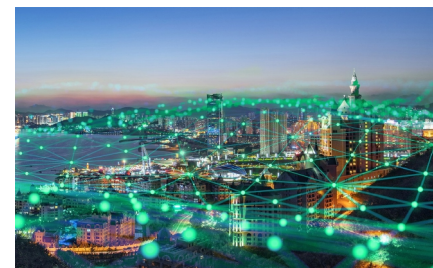
Established under the Ecodesign for Sustainable Products Regulation (EU) 2024/1781, the Digital Product Passport is a digital container of product information designed to strengthen supply chain transparency, support more informed consumer choices and facilitate compliance across the Single Market. While product data

is stored in a decentralized manner, economic operators must register each Digital Product Passport in the Registry, which provides the secure infrastructure needed to register unique product identifiers and associated metadata. ■

The EU Energy Performance of Buildings Directive (EPBD) Is Coming

led-professional.com/all/the-eu-energy

Europe aims to become climate-neutral by 2050 under the European Green Deal. A key pillar of this initiative is the revised European Energy Performance of Buildings Directive (EPBD), which all 27 EU Member States are required to implement beginning in 2026.



The EPBD is designed to improve the energy performance of public and commercial buildings, with lighting playing a critical role. The numbers highlight the opportunity: buildings currently account for approximately 40% of Europe's total energy consumption. To address this challenge, the European Union has launched its Renovation Wave initiative to accelerate the modernization of existing buildings and improve their energy efficiency. Under the EPBD, all non-residential buildings with HVAC systems exceeding 290 kW must be equipped with a lighting control system featuring data exchange interfaces by 2028. Beginning in 2030, this requirement will also apply to buildings with HVAC systems larger than 70 kW, which must additionally incorporate a Building Automation and Control System (BACS). ■

The Global Information Hub for Lighting Technologies & Design

LED professional is the comprehensive publication and platform, connecting experts in the design, testing, production and commercial application of the latest lighting technologies & design information from around the world.



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In Memoriam Armin Wezel

It is with great sadness that we learned of the passing of our long-time colleague and friend, Armin Wezel.

For more than 20 years, Armin served as a valued representative of *LEDprofessional*. What began as his responsibility for the German market gradually expanded to include the DACH region and, later, parts of Eastern and Southern Europe. Through his exceptional commitment, outstanding customer relationships, and extensive expertise in publishing, advertising, and events, he played an important role in the international development of our publications.

After graduating from business school, Armin began his career with an apprenticeship in newspaper and magazine publishing at Südkurier in Konstanz. Following his military service, during which he served as a Reserve Lieutenant, he gained experience in human resources before dedicating himself to the publishing industry.

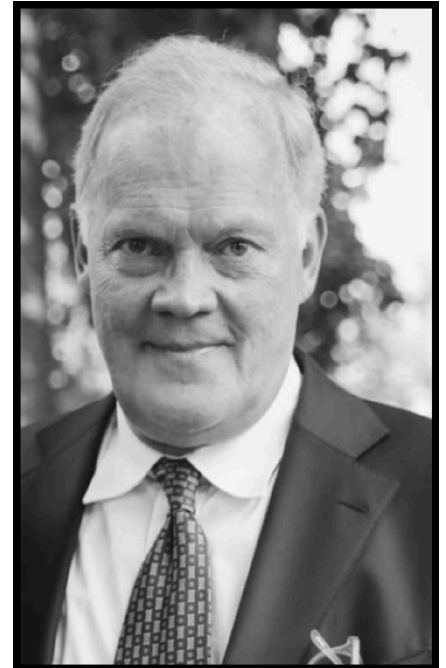
Throughout his career, Armin held senior sales and management positions with several respected publishing houses, including Jahreszeiten Verlag, Rhenania Fachverlag, Schwarzer Verlag, and ZM Communications. Between these appointments, he successfully worked as an independent sales representative, building an outstanding reputation throughout the publishing and advertising industry.

To us, Armin was far more than an experienced representative. His professionalism, reliability, integrity, and warm personality made working with him a genuine pleasure. He had a remarkable ability to build lasting relationships based on trust and mutual respect, and he was highly regarded by colleagues, customers, and partners alike.

With Armin Wezel, we have lost not only an outstanding professional but also a trusted colleague and dear friend. We are deeply grateful for his many years of dedication, loyalty, and invaluable contribution to *LEDprofessional*.

Our heartfelt condolences go to his family and loved ones during this difficult time.

Armin will be greatly missed and fondly remembered.



**Siegfried Luger and the
LEDprofessional Team**

From Human Centric Lighting to HCL-Ready Systems: Reflections and Next-Step Actions from deLIGHTed Talks Asia 2026

Lawrence Lin, Board Member, Good Light Group; Chairman, Good Light Group Asia; CEO, Lighting Recipe Studio

Human Centric Lighting (HCL) has reached a turning point. The scientific relevance of light for vision, circadian regulation and acute responses such as alertness is now broadly recognized, while claims related to sleep, mood and well-being should be translated into practice with appropriate caution. The discussions at deLIGHTed Talks Asia 2026, including the FG-05 and FG-06 focus group exchanges, highlighted a common challenge: the lighting industry does not simply need more inspiration about why light matters; it needs a practical translation layer that allows good light to be specified, designed, delivered, commissioned, verified and operated.

This article proposes the concept of HCL-ready systems as a bridge between science, standards, products, design software, controls, building operation and field verification. It argues that HCL should not be treated as a single product category or a marketing claim, but as a system-readiness condition supported by spectral data, photometry, color quality, temporal light modulation, eye-level exposure, spatial context, controls and operational feedback. For Asia, where manufacturing capacity is strong and project velocity is high, this transition represents both a responsibility and an opportunity: to move from component excellence toward evidence-based, user-centered lighting value.

A New Phase for Human Centric Lighting

Human Centric Lighting has been discussed for more than a decade, but the conversation has changed. In the early stage, the central task was awareness. The industry needed to understand that light is not only a visual utility and that the eye is not only a camera. Light entering the eye can support visual performance, shape perception, influence circadian timing, affect alertness and contribute to comfort and well-being. That message is no longer unfamiliar to most advanced lighting communities.

The challenge today is different. Many clients, designers, manufacturers and standard organizations already agree that light matters for people. The more difficult question is how to make better light practical. How should a designer specify a solution that is not merely bright enough, but also spectrally appropriate, visually comfortable, temporally stable and responsive to the rhythms of use? How should manufacturers describe the relevant properties of LEDs, luminaires, drivers and controls in a form that design software and verification teams can actually use? How should an owner know whether a project delivered what was promised, not only on the first day but also during operation?

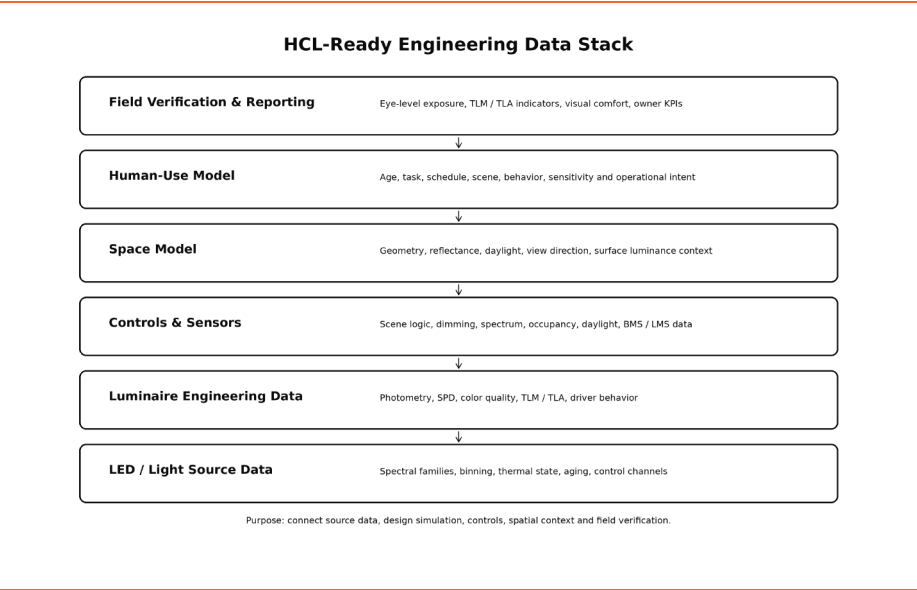
This was the background to deLIGHTed Talks Asia 2026. The event gathered scientists, standard organizations, lighting designers, manufacturers, controls specialists, smart building stakeholders and health-focused building communities. The strongest message emerging from the discussions was not that HCL needs another

slogan. It needs a more mature implementation pathway. In other words, the industry must move from Human Centric Lighting as an aspiration to HCL-ready systems as an engineering, design and verification reality.

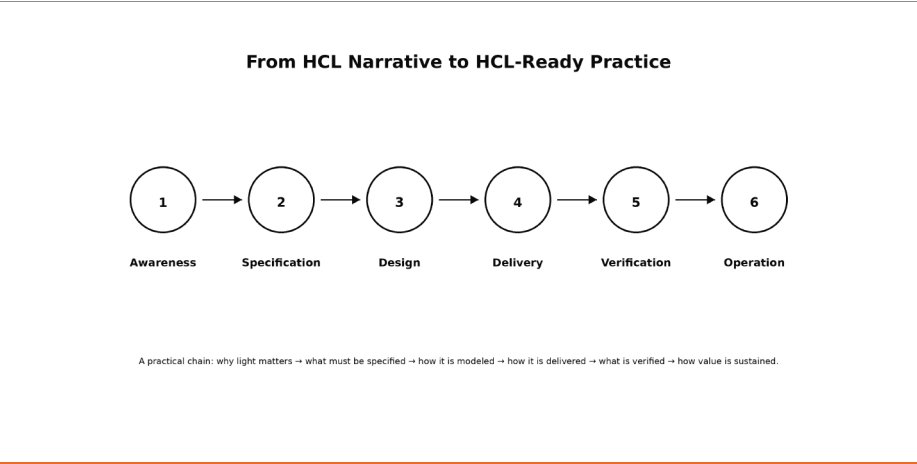
From “Good Light” to “Good Light That Can be Delivered”

The phrase “good light” is powerful because it keeps the focus on people. It reminds us that lighting is experienced by bodies, eyes, brains and communities, not by calculation grids alone. At the same time, the phrase can remain too broad if it is not connected to measurable and actionable parameters. Good light for a classroom at 9:00 a.m. is not the same as good light for a hospital ward at midnight. Good light for a senior care environment is not the same as good light for a young office worker seated next to a window. Good light must be understood through timing, spectrum, intensity, distribution, glare, temporal modulation, surface context, individual needs and operational intent.

The CIE has framed this challenge through the principle of delivering the proper light at the proper time, and CIE S 026/E:2018 provides the metrological basis for quantifying optical radiation for ipRGC-influenced responses. This is a major step forward because it gives the industry a shared language for melanopic and other photoreceptor-related quantities. WELL and other health-focused building frameworks have further helped bring eye-level exposure into mainstream project discussions.



HCL-ready engineering data stack. The proposed translation layer connects source data, luminaire data, controls, space modeling, human-use assumptions and field verification. Credit: Lawrence Lin / Lighting Recipe Studio.



From HCL narrative to HCL-ready practice. The industry transition requires a chain from awareness to specification, design, delivery, verification and operation. Credit: Lawrence Lin / Lighting Recipe Studio.

However, a standard metric is not the same as a finished implementation system. Even when melanopic equivalent daylight illuminance (mel-EDI), melanopic daylight efficacy ratio (mel-DER), color rendition metrics and temporal-light-modulation / temporal-light-artefact indicators are available, they often remain fragmented. Designers receive photometric files but not complete spectral or temporal behavior. Manufacturers may have spectral data but not in a form that travels through the design and commissioning workflow. Controls may be able to dim and tune, but the relationship between control scenes and human-centered design objectives is rarely documented in a verifiable way. Field measurements are often performed late, if at all, and are not always connected back to the design intent.

This is the central gap: we have many pieces of the puzzle, but not yet a robust translation layer between scientific knowledge and daily lighting practice.

Three Implementation Gaps

The first gap is the metric gap. Traditional lighting design has been built mainly around photopic illuminance, luminous intensity distribution, uniformity, glare indices and energy performance. These remain essential. HCL does not replace visual lighting quality; it expands the set of questions. A healthy and comfortable space still needs appropriate task visibility, luminance balance, glare control and color quality. But the design language must also include spectral effectiveness, timing, ver-

tical exposure at the eye, temporal light modulation and the specific use scenario.

The second gap is the data gap. The lighting industry has long relied on standard photometric data files such as IES and EU-LUMDAT formats. These files have enabled a huge ecosystem of design simulation and product comparison. Yet they were not originally created to carry the full set of information now required for HCL. A photometric distribution can tell us how much light goes where, but it does not fully describe spectral power distribution across operating states, melanopic ratios, color rendition across tuning channels, temporal light modulation behavior under dimming, driver response, control logic, sensor interaction or changes over lifetime. When these data remain outside the design file, HCL becomes difficult to model before installation and difficult to verify after installation.

The third gap is the verification gap. Many lighting projects are still judged by design intent, catalog claims or horizontal illuminance checks. HCL requires a more human-centered verification approach. Measurements must move closer to the eye position and to the actual viewing direction of occupants. They must account for time of day, control scene, daylight contribution, surface reflectance and operating conditions. Temporal light modulation should be measured not only at the product bench but also in the installed system, where dimmers, drivers, sensors, emergency circuits and controls can interact in unexpected ways. Without verification, HCL remains a promise. With verification, it can become a design discipline.

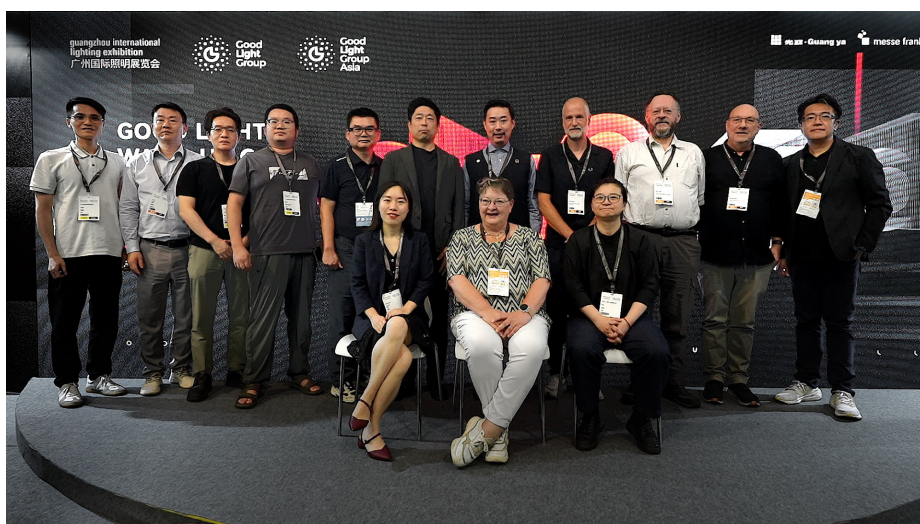
HCL-ready Systems: A Practical Framing

The term HCL-ready systems is proposed here as a practical framing. It does not mean that a product alone can guarantee a human outcome. It means that the product, data, control logic, design workflow and verification method are prepared to support human-centered lighting objectives in a transparent and interoperable way.

An HCL-ready system begins with LED or light-source data. This includes not only nominal CCT and CRI, but spectral power distribution, spectral stability, channel architecture, binning, thermal behavior and aging assumptions. For tunable systems, each operating state and mixed-channel state should be describable in a way that supports both visual-lighting calculations



deLIGHTed Talks Asia 2026 discussion setting. Plenary / panel photo showing international experts and Asian industry stakeholders in dialogue. Credit: GLGA / deLIGHTed Talks Asia 2026 / GILE.



FG-05 / FG-06 action discussion. Focus group / working session photo showing the discussion on HCL-ready engineering data, design workflow and verification. Credit: GLGA / deLIGHTed Talks Asia 2026.

and ipRGC-influenced / integrative-lighting quantities.

The next layer is luminaire engineering data. Photometry remains essential, but it should be connected to spectral, color quality and temporal behavior. A luminaire may have excellent photometric efficiency but still fail to support a target melanopic exposure at the eye. Another luminaire may offer a high melanopic ratio but create unacceptable glare or poor visual comfort if applied without spatial context. The useful question is not whether one parameter is high or low in isolation, but whether the combined system can deliver the intended luminous environment.

Controls and sensors form the third layer. HCL is often dynamic. It may require time-based scenes, daylight-responsive adjustment, personal control, occupancy logic or integration with building management systems. Yet a control system is only HCL-ready if its scenes are connected to measurable targets. A “morning scene” should not be just a label in an app. It should correspond to a documented range of eye-level exposure, spectrum, CCT, intensity, glare control and temporal stability under real conditions.

The fourth layer is the space model. Light is transformed by architecture. Surface reflectance, geometry, furniture, window position, daylight, view direction and oc-

cupant posture all change exposure. A luminaire cannot be evaluated as if it were floating outside the room. HCL-ready design therefore needs a spatial model that considers vertical and cylindrical quantities, surface luminance relationships, daylight variability and the difference between task plane light and eye-level light. The fifth layer is the human-use model. The same lighting condition can be appropriate or inappropriate depending on age, task, schedule and biological timing. A school, office, hospital, retail store and home all require different assumptions. Even within one building, scenes may need to support alertness, relaxation, wayfinding, recovery, night safety or visual precision. The human-use model does not need to overclaim medical outcomes. It should define the intended lighting support for a defined use case.

The final layer is field verification and reporting. A system is HCL-ready only if the design intent can be checked after installation and maintained in operation. This includes measurements of photopic illuminance, melanopic EDI or related quantities, spectral characteristics, color quality, and temporal light modulation / temporal light artefact indicators such as PstLM for flicker perception and SVM for stroboscopic visibility, where applicable. It should also include evidence that controls deliver the planned scenes. Verification should be understandable by designers, owners and operators, not only by laboratory specialists.

What an HCL-ready Data Model Should Carry

An HCL-ready data model does not need to replace every existing lighting data format. A more realistic path is to define a complementary layer that can travel with, link to or extend current photometric and product data. The purpose is not to make product information more complicated for its own sake, but to make the information useful across the project life cycle.

At the source level, the model should carry spectral power distribution for relevant operating states, channel information for tunable products, color point behavior, melanopic ratios or melanopic DER, and assumptions about measurement conditions. At the luminaire level, the model should connect these spectral data to photometry, luminous flux, optical distribution, color rendition, electrical behavior and thermal conditions. At the driver and control level, it should describe dimming range, dimming method, temporal light modulation behavior under representative dim-

ming points, scene definitions and control-channel mapping. At the space level, the model should allow design software to calculate not only horizontal illuminance, but also vertical eye-level exposure and spectral results under defined scenes.

The most important part is traceability. If a designer specifies a daytime scene intended to support a given eye-level melanopic exposure, the project team should be able to trace that intent to product data, control settings, commissioning measurements and an operation record. If a luminaire is replaced, a driver is changed or a control scene is adjusted, the impact on the HCL intent should be visible. This is how HCL becomes maintainable rather than decorative.

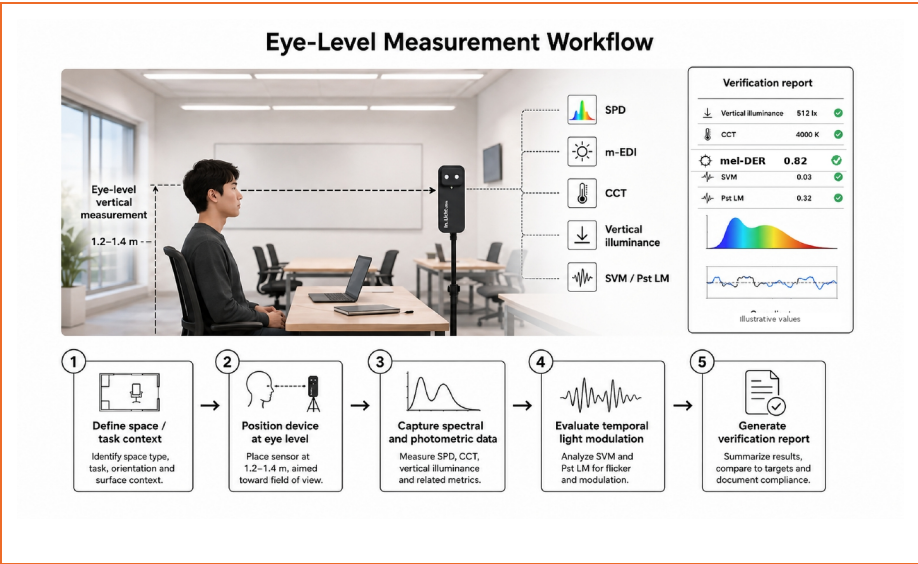
Such a model should also distinguish between required data and advanced data. A basic HCL-ready profile may include photometry, SPD, color quality, temporal light modulation / temporal light artefact indicators and recommended control states. An advanced profile may include aging curves, multi-channel spectral mixing tables, uncertainty information, surface-reflectance assumptions, daylight-responsive scene logic and API links to building operation data. This layered approach would allow small manufacturers and large global suppliers to participate without forcing every company into the same level of complexity on day one.

The underlying principle is simple: if a parameter is used to make an HCL claim, it should be represented in the data chain and should be verifiable in the field. This is the practical meaning of readiness.

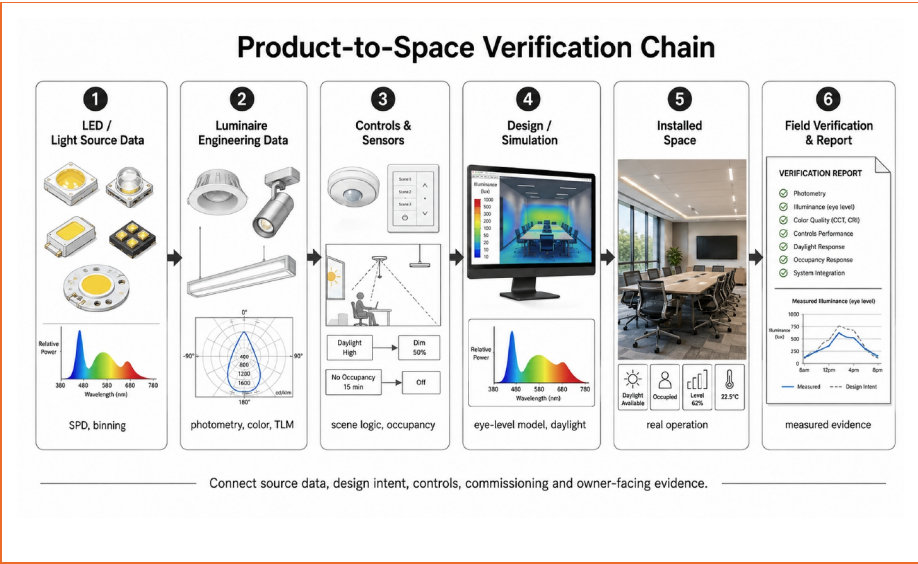
What FG-05 and FG-06 Suggested for Next-step Action

The FG-05 and FG-06 discussions at de-LIGHTed Talks Asia 2026 were valuable because they did not treat HCL as a purely academic topic. The participants focused on the missing practical bridge between knowledge and delivery. Several action directions emerged.

First, the industry needs to explore an HCL-ready engineering data model. This should not be rushed into a formal standard before the scope is tested. A pre-standard alignment phase is more appropriate. The purpose would be to define what data should be carried from LED to luminaire, from luminaire to controls, from controls to design software and from design software to verification. The model



Eye-level measurement workflow. Field measurement workflow at occupant eye height showing spectral, melanopic and temporal-light-modulation / temporal-light-artefact metrics. Values shown are illustrative. Credit: Lighting Recipe Studio / GLGA.



Product-to-space verification chain. The diagram illustrates how LED source data, luminaire engineering data, controls, design simulation, installed-space operation and field verification can be connected into a traceable HCL-ready workflow. Credit: Lighting Recipe Studio / GLGA.

should respect existing standards and file formats while identifying where extensions or complementary data structures are needed.

Second, pilot projects should be used as learning platforms. The next generation of HCL pilots should not only demonstrate attractive scenes. They should document the full chain: design intent, product data, control settings, simulation assumptions, commissioning measurements, occupant-use scenarios and operational feedback. Schools, healthcare environments, workplaces and residential settings are especially useful because their human-use requirements are clear and their lighting conditions affect daily life.

Third, measurement should become a normal part of the workflow. The industry cannot improve what it does not measure. Spectral measurement, eye-level exposure measurement and temporal modulation measurement should become more accessible to designers, commissioning teams and building operators. This does not mean that every project must become a laboratory study. It means that critical claims should be supported by practical evidence.

Fourth, education must change. Many manufacturers still communicate HCL through CCT, CRI and vague wellness language. Many designers understand visual lighting but do not yet have easy tools for

melanopic exposure, spectral trade-offs or temporal modulation. Many owners want health value but do not know how to specify or verify it. Training must therefore be cross-disciplinary. The goal is not to turn every designer into a chronobiologist, but to give the industry enough shared literacy to avoid superficial claims and support responsible practice.

Fifth, owner value must be made explicit. HCL cannot scale if it is presented only as a technical ideal. Building owners need to understand why better lighting matters for occupants, brand, certification, risk reduction, satisfaction, adaptability and long-term operation. The value proposition must be honest. HCL should not promise simple medical outcomes, but it can support environments that are more aligned with human needs, easier to operate and more transparent in performance.

Why Asia Matters

Asia has a special role in this transition. The region contains a large share of the global lighting manufacturing ecosystem, strong supply chains, fast product development capability and increasingly sophisticated project markets. This creates both opportunity and risk.

The opportunity is that Asia can help make HCL practical at scale. If LED, driver, luminaire, control and sensor manufacturers begin to provide better engineering data, global design practice can change quickly. If major Asian brands move from parameter competition to system-level value, the market can shift from “brighter, cheaper,

faster” toward “measurable, comfortable, health-oriented and verifiable.”

The risk is that HCL becomes another marketing label attached to ordinary products. If that happens, trust will be lost. Overuse of claims such as “healthy light” without measurement, context or verification will weaken the credibility of the entire field. The answer is not to avoid the language of health and well-being, but to discipline it. Claims should be proportional to evidence. Specifications should be clear. Measurement methods should be transparent. The user should remain at the center.

This is why the conversation at deLIGHTed Talks Asia felt timely. International scientific and standards communities are developing the language. Designers are asking for tools. Manufacturers are searching for differentiation beyond price. Owners are increasingly aware of health, experience and ESG. The next step is to connect these communities through practical, shared infrastructure.

Avoiding Two Extremes

As HCL matures, the industry should avoid two opposite extremes. The first is reductionism: reducing HCL to a single number. Melanopic EDI is important, but it is not the whole lighting experience. A space can reach a melanopic target and still be uncomfortable because of glare, poor luminance distribution, bad color quality or excessive temporal modulation. A single number is useful only when it is embedded in a complete design context.

The second extreme is vagueness: using human-centered language without measurable commitment. If every warm, pleasant or tunable luminaire is described as HCL, the term loses meaning. The field needs enough rigor to distinguish between general comfort lighting, wellness-inspired marketing and genuinely HCL-ready systems.

A balanced approach is possible. HCL should be science-informed but not scientifically arrogant; practical but not simplistic; measurable but not blind to lived experience. The goal is to create luminous environments that support people in real spaces, under real schedules, with real products and controls.

A Proposed Roadmap

A practical roadmap can be summarized in six steps.

The first step is awareness: communicating why light affects people beyond visibility. This step remains important, especially for owners and the wider public, but it is no longer sufficient for professional practice.

The second step is specification: defining the relevant metrics for each project type. These may include photopic illuminance, luminance distribution, glare control, color rendition, spectral data, melanopic quantities, temporal modulation, daylight contribution and control requirements.

The third step is design: integrating those metrics into simulation and decision-making. HCL should be considered early, not added after the lighting layout is fixed. Design software and data formats must evolve so that designers can evaluate not only horizontal task-plane illuminance, but also eye-level exposure and spectral conditions.

The fourth step is delivery: ensuring that products, drivers, sensors and controls perform as expected. This requires better data from manufacturers and clearer coordination between lighting, controls and building systems.

The fifth step is verification: measuring the installed environment under representative conditions. Verification should not be a punitive exercise; it should be a feedback loop that improves design, commissioning and operation.

The sixth step is operation: maintaining performance over time. HCL is not a static certificate attached to a product. Buildings change. Occupants change. Daylight

Asia as an HCL Implementation Bridge



Asia as an HCL implementation bridge. The diagram illustrates the role of Asia in connecting manufacturing capacity, project delivery, design practice and global standards dialogue. Credit: GLGA / deLIGHTed Talks Asia 2026.

changes. Controls drift. A mature HCL system should support ongoing observation, adjustment and reporting.

Conclusion: No Verification, No Credible HCL Practice

Human Centric Lighting has inspired the industry to look beyond energy and visibility. That inspiration remains valuable. But the next phase requires a more disciplined and collaborative effort. We need to connect science with standards, standards with engineering data, engineering data with design software, design software with controls, controls with field verification and verification with owner value.

The phrase “HCL-ready systems” is offered not as a final standard, but as a practical bridge. It asks whether a lighting solution is ready to be described, modeled, delivered, measured and operated in a way that supports human-centered objectives. It shifts the conversation from isolated claims to system readiness.

The discussions at deLIGHTed Talks Asia 2026 showed that the industry is ready for this shift. The task ahead is to build the translation layer together. Scientists, standard organizations, designers, manufacturers, controls providers, software developers, certification bodies and building owners all hold part of the answer.

Good light must be more than a beautiful idea. It must become designable, deliverable, interoperable and verifiable. Without verification, there is no credible health-oriented lighting claim. With verification, HCL can move from promise to practice. ■



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Sunlight, UVB and Vitamin D – Human Centric Lighting Beyond Melanopic Stimulation

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UVB radiation initiates vital processes in our body, one of which is the production of vitamin D in the skin. It is well known that over-exposure to the sun may bring a risk. Less well known is that the same is true for insufficient sun exposure due to our indoor lifestyle. In Part 1 of this article, we first describe the scientific understanding behind vitamin D. In Part 2 we describe how artificial light can be enriched with a safe, low dose of UVB, to supplement natural vitamin D production in the skin. Not too much, not too little.

Part 1: The Biology Behind Vitamin D

Light is a fundamental part of life on earth [1,2], as important as food, air and water. The feeling of sunlight has a profound effect on people's health and wellbeing, supporting our visual, emotional and biological processes. Part of that radiation is perceived as visible light, while other parts, like UV (ultra-violet) and IR (infra-red) are invisible for us, but not meaningless. Infrared brings us warmth and comfort, while UV can bring us the "sunshine vitamin". On the other hand, overexposure to sunlight can bring sunburn. For most people knowledge ends there. When discussing Human Centric Lighting and its effect on our circadian rhythm (sleep-wake cycle), we often point out that people spend more than 90% of their time indoors [3]. This same fact is equally important when considering outdoor UVB exposure for maintaining sufficient vitamin D levels.

Research clearly shows that vitamin D levels vary throughout the year and that many people have insufficient vitamin D even during the summer months (Figure 1). Because modern lifestyles keep us indoors most of the time, and because sun-avoidance practices are common in many countries, a large proportion of the world's population simply does not get enough vitamin D.

A recent global meta-analysis, based on blood measurements collected between 2000 and 2022, found that approximately 77% of people have insufficient vitamin D levels [4]. While it is often assumed that vitamin D deficiency is mainly a problem in countries at higher latitudes (i.e. further away from the equator), this is no longer the case.

Modern lifestyles mean that people spend most of their time indoors, regardless of where they live. In addition, in regions closer to the equator, high temperatures, humidity, and the growing impact of climate change can discourage people from spending time outdoors. As a result, vitamin D insufficiency is widespread across the globe.

The same study [4] showed that even in equatorial regions (between 20° south and 20° north latitude), more than 52% of people have insufficient vitamin D levels. Outside these regions, the prevalence is even higher, typically ranging between 75% and 85%.

Most people know that vitamin D levels tend to decrease during the winter months. As shown in Figure 1, vitamin D concentrations in winter can be as much as 50% lower than the levels typically reached during the summer. This seasonal variation highlights how strongly our vitamin D status

depends on exposure to sunlight throughout the year.

Figure 2 shows a typical daylight spectrum, including visible light, infrared radiation, and ultraviolet (UV) radiation. UVC radiation is completely absorbed by the ozone layer and does not reach the Earth's surface [6]. UVB radiation is only partially absorbed and plays a key role in the production of vitamin D in the skin [6,7]. In contrast, UVA radiation is largely unaffected by the atmosphere.

The amount of UVB reaching the Earth depends on several factors, including latitude, altitude, ozone concentration, weather conditions, air pollution, and the time of day and year [8,9]. The two graphs in Figure 2 compare summer and winter conditions at a latitude of 50°N under clear-sky conditions.

The graphs show that winter sunlight is not only less intense overall but also contains relatively less UVB radiation. This is because the sun is lower in the sky during winter, causing sunlight to travel through a thicker layer of atmosphere and ozone, which absorbs more UVB [10]. As a result, UVB exposure in winter can be about 26 times lower than in summer, while visible light levels (lux) decrease by only about a factor of four.

In real-world conditions, the reduction in UVB exposure is often even greater because winter months typically have more cloudy and overcast days [11,12]. This large seasonal drop in UVB availability helps explain why vitamin D levels decline so significantly during the winter period. Also, due to lower temperatures we expose less skin to sunlight.

More than 80% of our vitamin D is produced through exposure to sunlight [13],

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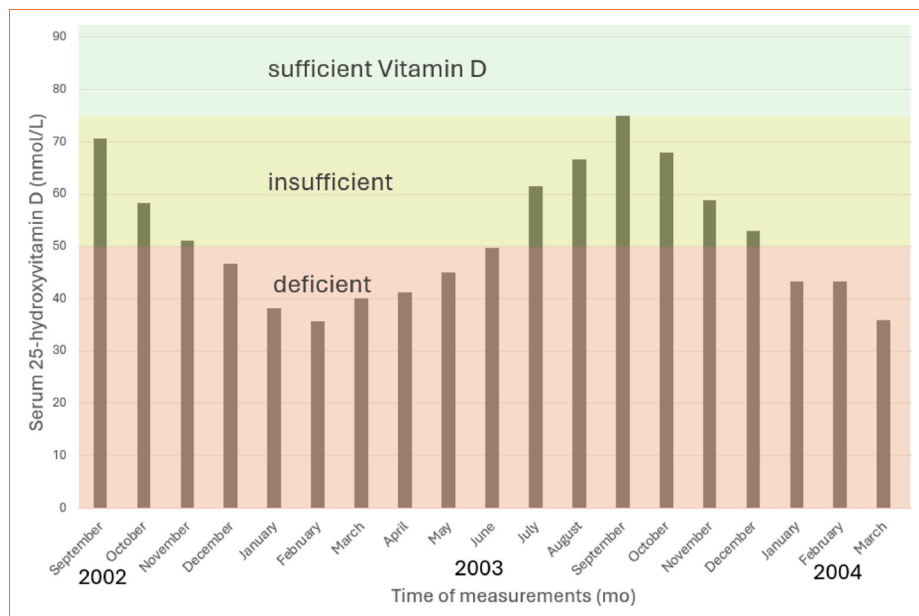


Figure 1: Seasonal variation in average vitamin D levels in a UK cohort (after [5]), obtained from blood analysis. Indicated are three regions of the vitamin D level: sufficient (>75 nmol/L), insufficient (50-75 nmol/L) and deficient (< 50 nmol/L). Note that in wintertime vitamin D deficiency is common.

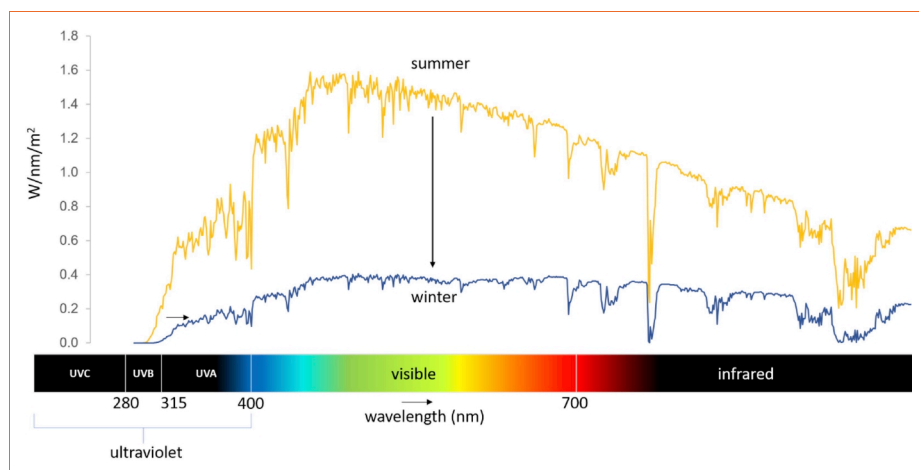


Figure 2: Intensity of solar radiation as a function of wavelength, at noon on June 21 and December 21, on a horizontal surface at sea level, at latitude 50° N (after [9]). Note the intensity difference for summer and winter time, and the shift in the ultraviolet region.

while food contributes only a relatively small amount. As a result, maintaining healthy vitamin D levels through diet alone is difficult, and long-term supplementation is often needed when sunlight exposure is insufficient.

Once vitamin D is produced in the skin, it is converted in the liver and kidneys into its biologically active form. In this active state, vitamin D functions as a steroid hormone that plays an important role in health and wellbeing, influencing the function of many tissues and cells throughout the body.

Unfortunately, vitamin D levels have declined significantly since the 1970s. Several

factors associated with modern lifestyles are thought to contribute to this trend:

- More people now live in urban environments rather than rural areas, where UVB exposure is often lower.
- A growing proportion of jobs are performed indoors instead of outdoors.
- In warmer climates, the widespread availability of air conditioning encourages people to spend more time inside.
- Increased use of indoor entertainment and digital media, such as television, gaming, and internet-based activities, has reduced time spent outdoors, particularly among children.
- Concerns about skin cancer have led many people to avoid direct sun expo-

sure or to take extensive sun-protection measures.

Together, these lifestyle changes have substantially reduced the amount of UVB radiation people receive from sunlight, contributing to the widespread prevalence of low vitamin D levels observed today.

Data from the U.S. National Health and Nutrition Examination Survey (NHANES) show a significant decline in blood vitamin D levels between the 1988–1994 and 2001–2004 survey periods [14]. Over just one decade, the proportion of the population with sufficient vitamin D levels (≥ 75 nmol/L) decreased substantially.

The study concluded that existing recommendations for vitamin D supplementation may not be sufficient to address the increasing prevalence of vitamin D insufficiency.

This decline in vitamin D status is also reflected in the re-emergence of rickets (soft and weak bones), a disease caused by severe vitamin D deficiency. Studies from Japan [15] and the United Kingdom [16] have reported a threefold and fourfold increase, respectively, in the number of rickets cases over the past decade.

These findings suggest that vitamin D insufficiency is becoming more common. Reduced exposure to sunlight, combined with insufficient vitamin D supplementation, is believed to be a major contributing factor to this trend.

Important Notice of Supplementation vs UV Exposure

It is commonly assumed that vitamin D obtained through sunlight exposure and vitamin D obtained through food or supplements follow the same biological pathways and therefore provide the same benefits. As a result, taking vitamin D supplements during the winter is often considered a straightforward substitute for reduced sun exposure, and partly, it is.

However, there are several reasons to believe that vitamin D produced naturally in the skin through exposure to sunlight may offer broader biological benefits than vitamin D obtained through supplements alone.

Three key differences have been identified:

- *Interaction with other biological pathways*
The production of vitamin D in the skin is closely connected to several other important biological pathways. The pre-

cursor molecule 7-dehydrocholesterol (7-DHC or pre-vitamin D), which is converted to vitamin D upon exposure to UV radiation, can alternatively be transformed by enzymatic processes into cholesterol (Figure 3). Cholesterol, in turn, serves as the precursor for a wide range of hormones, including cortisol. Studies have shown that cortisol levels exhibit seasonal variation, with concentrations generally higher during winter than during summer [17]. The substantial reduction in UV exposure during the winter months may contribute to increased synthesis of stress-related hormones such as cortisol. These interconnected metabolic pathways may also be influenced by circadian rhythms, with certain processes being more active during daytime and others predominating at night. Consequently, vitamin D supplementation may not replicate all of the complex biological interactions that are naturally triggered by sunlight-induced UV exposure.

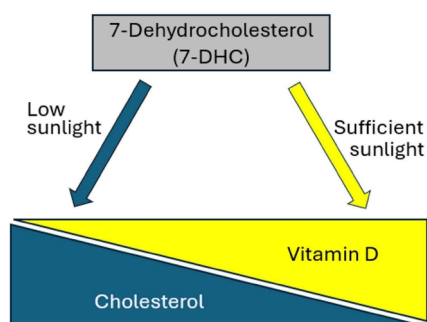


Figure 3: Model for synthesis of vitamin D and cholesterol, from 7-DHC (pre-vitamin D) depending on sunlight exposure (after [18]). Note that the synthesis of cholesterol and vitamin D in the skin are utilizing the same precursor molecule.

- *Production of additional biologically active compounds*

Sunlight-induced vitamin D synthesis in the skin produces not only vitamin D itself, but also a range of related vitamin D derivatives (like various lumisterol and tachysterol molecules) that may contribute to health and wellbeing [19]. These compounds are generally not present in conventional vitamin D supplements. Furthermore, research [20] may suggest that the specific derivatives produced may vary throughout the day as the UVB spectrum of sunlight changes, indicating a dynamic relationship with the body's circadian rhythm that is difficult to replicate through supplementation.

- *Differences in transport and delivery within the body*

Vitamin D produced in the skin is transported and distributed through the body differently than vitamin D absorbed through the digestive system [21]. Studies

suggest that these differences may affect the biological activity, effectiveness, and duration of action of vitamin D, potentially favoring the naturally synthesized form.

These distinct metabolic pathways may partly help explain why observational studies often show strong associations between sunlight exposure and health outcomes, while supplementation studies sometimes produce less consistent results.

While the risks of excessive sun exposure are widely recognized, the potential consequences of insufficient sun exposure receive much less attention.

This raises an important challenge: how can we obtain the benefits of UVB exposure while minimizing its risks? One possible approach is the use of artificial lighting enriched with carefully controlled, low doses of UVB radiation—providing enough exposure to support beneficial biological processes without exceeding safe limits. In other words, the goal is to achieve a balance: not too much, and not too little. This is visualized in a biphasic dose-response curve as shown in Figure 4.

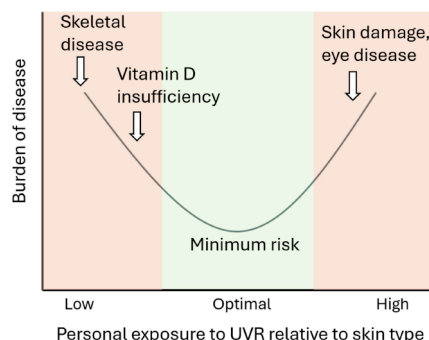


Figure 4: Schematic diagram of the relation between ultraviolet radiation (UVR=UVA+UVB) exposure and the burden of disease (after [22]).

UV Benefits Beyond Vitamin D

In recent years, research has revealed that UV exposure activates many more metabolic pathways in the skin beyond the well-known production of vitamin D and its derivatives. These other pathways generate a variety of biologically active compounds that may provide systemic health benefits throughout the body through mechanisms that are independent of vitamin D.

As a result, the strong associations often observed between good health outcomes and high vitamin D levels may not be due solely to vitamin D itself but could also reflect the activity of these other UV-induced biological processes. Consequently, increasing vitamin D levels through supplementation may not necessarily provide all

the health benefits associated with natural UV exposure, as it does not activate the full range of pathways triggered by sunlight.

UV light from the sun on the skin produces a variety of biologically active substances, including hormones, hormone-like compounds, immune signaling molecules, and neurotransmitters. These substances include stress-related hormones and peptides such as cortisol, ACTH (adrenocorticotrophic hormone), β -endorphin, and melanocyte-stimulating hormones (MSH), as well as other molecules like nitric oxide (NO), melatonin metabolites, and other compounds derived from amino acids. Many of these molecules can enter the bloodstream and influence organs throughout the body, including the brain, immune system, and endocrine glands [23].

As a result, UV exposure can affect much more than just vitamin D levels. It helps regulate a wide range of biological functions that contribute to overall health and well-being. These effects depend on the wavelength of UV light and involve complex interactions between the skin, the brain, the immune system, and other organs. Because of these multiple pathways, vitamin D supplements (pills) alone may not replicate all the health effects associated with natural sunlight exposure.

Benefits of Sufficient UV Exposure and Vitamin D Levels

Vitamin D is an essential hormone that helps the body function properly. Its most important and scientifically established role is to help the body absorb and use calcium and phosphorus, two minerals that are vital for strong bones and teeth. Calcium also acts as a universal messenger inside cells. Virtually every cell type uses carefully controlled calcium signals to regulate processes such as muscle contraction, hormone secretion, neurotransmitter release, gene expression, cell growth, and energy production in mitochondria. Without sufficient vitamin D, the body cannot efficiently absorb these minerals, even when they are present in the diet.

One of the best-known benefits of vitamin D is its contribution to bone health. During childhood, vitamin D is necessary for proper growth and development of the skeleton. In adults, it helps maintain bone density and supports the continuous process of bone renewal and repair. Severe vitamin D deficiency can lead to soft and weak bones, causing rickets in children and osteomalacia in adults. Long-term deficiency may also contribute to an increased risk of osteoporosis and fractures, particularly in older individuals.

Vitamin D also plays an important role in muscle function. Muscle cells contain vitamin D receptors, which means they can respond directly to vitamin D. Adequate vitamin D levels support muscle strength, coordination, and balance. People with low vitamin D levels often experience muscle weakness and reduced physical performance. In older adults, maintaining adequate vitamin D status has been associated with a lower risk of falls because of its positive effects on muscle function and stability.

In addition to supporting bones and muscles, vitamin D helps regulate the immune system. It stimulates the production of natural antimicrobial compounds that help the body defend itself against infections like e.g. influenza, flu and COVID19 [24]. Vitamin D also helps keep the immune response balanced, allowing the body to fight harmful microorganisms while avoiding excessive inflammation that could damage healthy tissues. Scientists have observed associations between low vitamin D levels and a higher risk of several infectious and immune-related diseases, although research is still ongoing to determine the extent of these effects in different populations.

The above-mentioned functions represent the classical and most widely accepted health benefits of vitamin D.

Part 2: Supplementing Artificial UVB

To find the “sweet spot” for providing enough, but not too much UVB via an artificial source, we first need to know how much UV is required for a sufficient vitamin D level. We took the common advice of several national and international organizations as the starting point. Although the general advice per region varies, we deduced an average advice of seeking outdoor sunlight exposure for about 15 min between 10:00 and 15:00h, 2 to 3 times a week, between April and September, exposing the face, neck and hands (and preferably also the lower arms). To estimate the solar exposure at these moments in time we use a published Excel spreadsheet model for calculating solar spectral irradiance [9]. This model provides the spectral irradiance on a horizontal surface at sea level for a clear sky, at any selected geographical latitude, month, day of the month, and time of day. The model separately calculates the direct irradiance from the sun and the indirect (diffuse) irradiance from the sky. Combined, they deliver the total irradiance. We developed a

custom method to convert from irradiance on the horizontal surface to the vertical surface, which is more applicable to the shape of a walking person. We took an average cloudiness (based on meteorological data) and an average sky visibility (obstruction from buildings and trees) into account. In **Figure 5** the result of this simulation is shown for a 15 min walk at three geographical latitudes (40°, 50°, 60°), at noon at day 15 in the month. The vertical axis shows the Standard Erythema Dose (SED) which is a standardized unit used to measure the amount of erythema weighted ultraviolet (UV) radiation a person's skin receives from the sun, regardless of their specific skin type or sensitivity [25]. 1 SED corresponds to 100 J/m² where the Joules are erythema weighted. As a rule of thumb, for the most sensitive skin type I (Fitzpatrick scale), a SED > 2 will initiate a sunburn. As **Figure 5** shows, a 15-minute walk will not exceed this sunburn threshold. As expected, at lower latitude (more close to the equator) the UV exposure is higher.

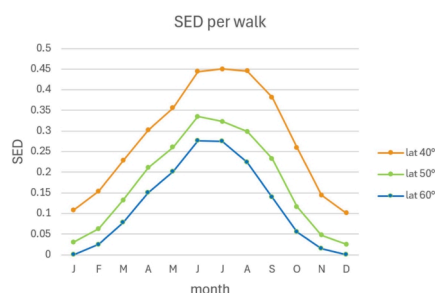


Figure 5: Standard Erythema Dose (SED) for a 15-minute walk around noon, on day 15 in the month, at three geographical latitudes. Basic irradiation from [9] was modified with a custom method for a walking person (see main text).

Measuring Solar Irradiance

Next, we validated the simulations by measuring actual UV exposure on regular walks during a year in Eindhoven (around 51° latitude). Polysulphone patches were used on the hands and underarms, and on the face (chin, nose, cheeks, forehead) during these walks (**Figure 6**). These patches are in fact wearable dosimeters to measure cumulative UV radiation exposure and were obtained through the group of Prof. Ann Webb (Manchester University). Unlike consumer stickers that change color instantly, these polysulphone patches require laboratory analysis. The amount of UV received is determined by measuring the patch's absorbance at 330 nm using an UV-VIS Edinburgh spectral device before and after UV exposure (the decrease in absorption is a measure for the UV dose).

In **Figure 7** we show the measured SED (body-surface weighted average from the different patches) across a full year as derived from analyses of the polysulphone

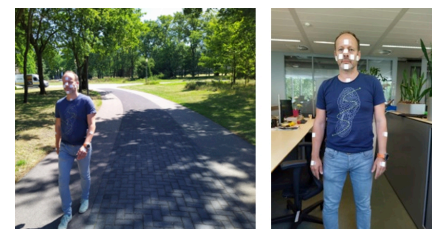


Figure 6: Measuring UV exposure using polysulphone patches (on the face, hands and lower arms) during a 15 min walk around noon (Eindhoven). From laboratory analysis of the patches, it is determined what the accumulated UV dose is.

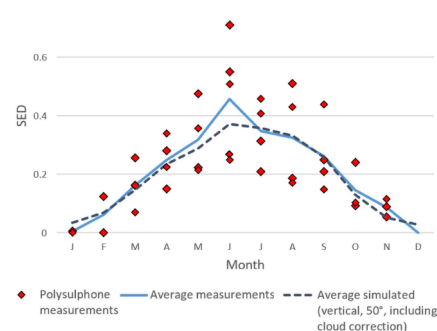


Figure 7: Comparison of measured and simulated SED values from 15-minute walks at noon across a year.

patches together with the simulations. It shows a very good resemblance between the average measurements and the simulation (Eindhoven is at 51.4° latitude, simulation is at 50°).

From Recommended Exposure to Low-dose Application

The average dose from a single 15-minute outdoor walk exposure is 0.28 SED. This number is obtained by averaging across the period April-September, and then correcting for the fact that between 10:00-15:00h the average solar irradiance is around 0.83 (with normalized value of 1 at 12:00h). The recommended weekly dose then is 2-3 times 0.28 SED, or $2.5 \times 0.28 = 0.70$ SED. If we want to deliver this weekly dose via UVB-enhanced light during office hours of a 5-day workweek, we arrive at a daily dose of $0.70 / 5 = 0.14$ SED. This is exactly the daily dose received in a clinical trial described below.

Proof of Effectiveness from a Clinical Trial

The effectivity of an ultra low dose UVB was tested in a clinical trial in the UK [26] during wintertime, when sunlight is too weak to support natural vitamin D production. From mid-October 2021 and March 2022 (20 weeks) a double blind randomized clinical trial with office workers in the Sunderland Hospital was conducted. Ten participants used standard desk lamps whereas another ten participants used

modified versions of the lamps that contained additional LEDs that emitted ultra low levels of UVB (**Figure 8**). Participants used the lamps during normal working hours, and their vitamin D levels were measured regularly. The UV exposure was extremely low and carefully designed to stay well within established safety limits. The average daily received exposure was 0.14 SED within an 8-hour working day. Results showed that participants using the UV enhanced lighting experienced a statistically significant improvement in vitamin D levels compared to those using regular lighting. Specifically, the UV group had about a 7 nmol/L higher vitamin D level after 8 weeks compared to the control group. It meaningfully reduced the usual seasonal drop in vitamin D seen during winter, over the 8-week test period.

Importantly, interviews with the participants after the study period revealed that the lighting was well tolerated. No adverse effects of the lighting were reported; on the contrary participants welcomed the additional lighting and even mentioned to prefer lighting above supplements (as it means they wouldn't forget to take them). Over-

all, the study demonstrates that integrating very low levels of UVB into everyday indoor lighting is a promising, practical way to support vitamin D levels during periods of low sunlight. This approach could offer a convenient alternative or complement to supplements, particularly for people with limited outdoor exposure.



Figure 8: Floor lamp providing white light at the desk, modified with LEDs emitting ultra-low levels of UVB.

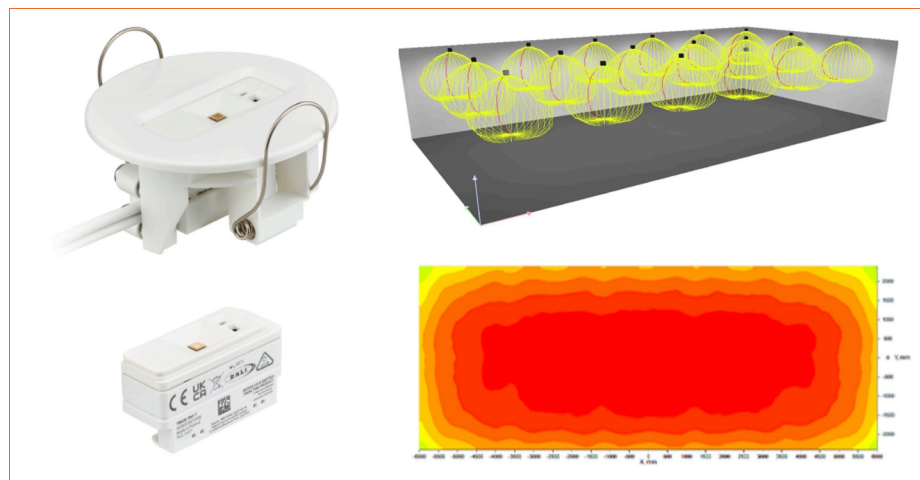


Figure 9: Left: The VitaUp module as standalone solution (upper picture) and the VitaUp module for luminaire integration (lower picture). Right: Optical simulation of a 3x6 grid of modules in an office space, showing uniform coverage at the desk level.

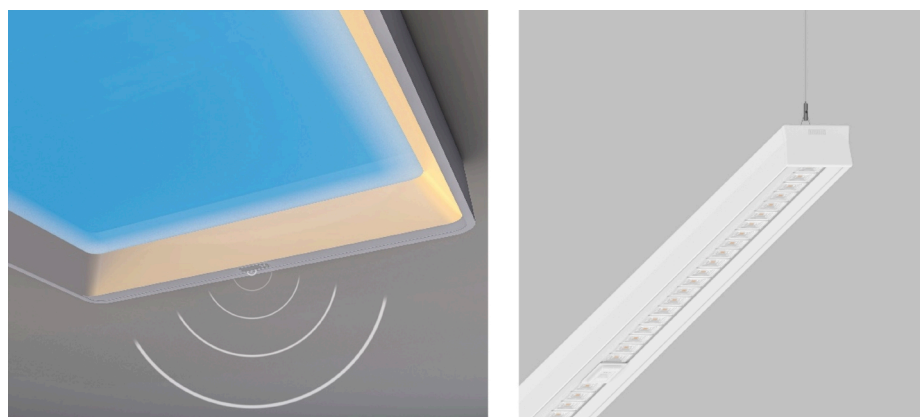


Figure 11: Two examples of integration of the VitaUp UVB module. Left: Philips Skylight with VitaUp module in the rim. Right: Regiolux Tirabo LumiD3 with the VitaUp module in the centre of the light emitting area.

Photobiological Safety

Light sources and luminaires need to comply with the photobiological safety standards [27]. For the UVB part, it requires to be compliant with the actinic irradiance requirements in accordance with IEC 62471. For a risk group 0 (exempt) classification the actinic weighted irradiance should be below 1 mW/m^2 . The defined exposure dose of 0.14 SED can be achieved, while remaining below the Risk Group 0 irradiance and exposure limits within normal (ceiling) use, making the application and luminaires safe to use. The knowledge has been applied to a specially designed UVB accessory from Signify: Philips VitaUp.

VitaUp Module

The above-described background research and analysis have led to the development of the Philips VitaUp module, containing UVB emitting LEDs. The module can be used as standalone (**Figure 9**). A grid of modules can be realized in an office space providing a uniform coverage within the room or can be implemented in a luminaire. Also, the module can be programmed to provide a circadian day profile. Sunlight UVR is naturally only available during daytime, not during the evening and night, so it makes sense to have a circadian profile in sync with nature.

In **Figure 10** the emission spectrum of the VitaUp module is shown. It is designed to co-align with the up flank of the natural UVB emission of outdoor sunlight, while at the same time having spectral overlap with the action spectrum of pre-vitamin D, as defined by CIE [28].

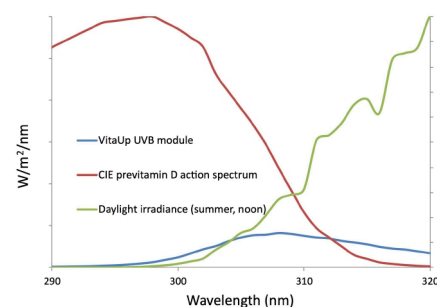


Figure 10: Normalized intensities of the pre-vitamin D (7-DHC) action spectrum (red line) as defined in CIE 2006 [28], summer daylight irradiance (green line), and the spectral emission of the VitaUp UVB LED (blue line).

Figure 11 shows two examples of luminaire architectures from Signify and Regiolux with an integrated Philips VitaUp module.

Final Remark

Recently, a group of international experts reviewed the latest scientific evidence on the health benefits of sunlight and ultraviolet radiation (UVR), particularly benefits that are not explained by vitamin D production alone [23]. Their review included findings from large population studies and a wide range of medical research. The experts noted that people who receive more sunlight exposure generally tend to have a longer life expectancy and a lower risk of several diseases. Growing evidence suggests that UVR may help prevent or improve certain health conditions, especially those involving inflammation and immune-system dysfunction. Based on the available scientific evidence, they concluded that the potential health benefits of sunlight deserve greater consideration in public health recommendations, and that preventive measures of natural and artificial UVB exposure might be a consideration. In addition to supporting the body's internal clock and vitamin D production, the UVB component of natural sunlight may offer health and well-being benefits that are largely absent from modern indoor environments. As people today spend most of their time indoors, incorporating selected beneficial aspects of natural sunlight into indoor spaces could represent a new and innovative approach to supporting human health and well-being. ■

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Dr. Ir. Marcel P. Lucassen is senior scientist in the field of Light & Vision. He holds a PhD in biophysics (on color constancy) from Utrecht University. Before joining Signify, he worked at several corporate and academic institutes, as well as in self-employment, specializing in color science and visual perception. In Signify Research he has been working on topics around Quality of Light and Human Centric Lighting, the last years with the emphasis on non-visual aspects of light, supporting Health and Wellbeing propositions.

 **Signify**

Biological-focused Indoor Lighting: Regiolux Expands Lighting Design with UV-B Technology

Regiolux

Nowadays, lighting design is no longer guided solely by visual comfort, energy efficiency and standards; in view of the globally widespread vitamin D insufficiency, biologically effective light has become a key design factor. With *LumiD³*, Regiolux adds a targeted spectral component – controlled UV-B radiation to support cutaneous vitamin D synthesis – safely and deliberately integrated into modern lighting concepts to enhance occupant well-being, especially when natural UV-B radiation is limited.



Alexander Ross, Innovation Manager at REGIOLUX, said: *“With *LumiD³*, we bring biologically relevant light back into indoor environments in a controlled, safely regulated, and predictable way. Our goal was to integrate UV-B technology into professional lighting design so seamlessly that it becomes a natural part of everyday operation, supporting human health and modern workspaces, requiring no additional effort from users while delivering tangible well-being benefits for contemporary workplaces.”*

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People spend up to 90 per cent of their day indoors. Whilst buildings meet the highest standards of comfort and energy efficiency, one biologically active component of light is almost entirely absent: UV-B radiation. People who spend long periods of time indoors, in particular, often receive only minimal natural UV-B exposure. UV-B radiation is a natural component of sunlight and triggers the body's own vitamin D synthesis. The new *LumiD³* module from Regiolux closes this gap with controlled, low-dose UV-B radiation. The system is not a medical device, but a lighting solution for work and communal areas where people spend long periods of time, such as in offices and administrative buildings, educational establishments or care homes.

To ensure safe use, a built-in timer automatically limits the operating time to a maximum of eight hours per day. Depending on the planned equivalent illuminance level of 1 to 4 lux, the UV-B exposure corresponds to an outdoor summer walk lasting between 4 and 16 minutes - indoor.

A proximity sensor deactivates the UV-B module when the distance is less than ten centimeters. Preset light profiles adapted to the seasons can optionally be used, for example from September to May. During the winter season, characterized by low solar altitude and shortened daylight periods, the human body receives only minimal exposure to UV-B radiation and is consequently almost entirely deprived of its essential photobiological radiation.

This is precisely when it's time for vitamin D support via indoor lighting. Manual operation is carried out via an intuitively labelled push-button switch, which allows the UV-B module to be switched on or off at any time as required. In a typical recessed ceiling installation, *LumiD³* operates within risk group RG0; even at closer viewing distances, risk group RG1 is not exceeded.



The *LumiD³* UV-B module is available in recessed and surface-mounted versions, allowing flexible integration into both new construction and retrofit projects.

LumiD³ is also easy to integrate into planning. Regiolux provides design recommendations for various room configurations – from individual workstations to open-plan offices. Project planning is based on equivalent illuminance levels and can be incorporated into existing lighting designs without any additional effort. IES and LDT data enable planning in Relux and DIALux as usual.

LumiD³ is available as a standalone UV-B emitter for recessed or surface-mounted installation and adds a targeted biological component to indoor lighting. As implemented in the Regiolux tirabo luminaire, the combination of Human Centric Lighting (HCL) and controlled UV-B closely approximates natural daylight: HCL supports circadian rhythm and daytime melatonin regulation, while UV-B promotes cutaneous vitamin D synthesis. This synergy creates a biologically focused lighting environment that enhances occupant well-being in the darker months.

The surface-mounted housing is also suitable for installation in exposed ceilings. Cut-outs on the front facilitate cable routing and enable quick installation. *LumiD³* thus



expands the possibilities for biologically oriented interior lighting.

Lighting designers, architects and electricians are provided with a solution that enables the controlled integration of UV-B radiation into existing or new lighting concepts in a simple, safe and reliable way.

To support planning and project design, Regiolux regularly offers webinars providing practical guidance on the use of *LumiD³* and its integration into modern lighting concepts. Join our next webinar on 22.10.2026. ■

Register here:

<https://www.regiolux.de/de/Service/KnowHow/Seminare>

Further information is available at

www.regiolux.de/en/UV-B,
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The *tirabo* luminaire (center image) is available with the factory-integrated *LumiD³* UV-B module, extending professional lighting systems with safely controlled UV-B exposure to support human health and well-being.

REGIOLUX GmbH is a German manufacturer of professional lighting solutions for commercial, industrial, educational, health-care, and public buildings. With decades of experience in lighting technology, the company develops energy-efficient luminaires and intelligent lighting systems that combine high visual quality, sustainability, digital connectivity, and well-being. Headquartered in Königsberg in Bavaria, REGIOLUX focuses on innovative solutions that enhance both building performance and occupant well-being.

How Changing the Color and Brightness of Indoor Light Across the Day Affects Melatonin and Sleep

Dr.-Ing. Oliver Stefani, Founder of Chronolight & Senior Scientist at the Lucerne University of Applied Sciences and Arts

Although Human Centric Lighting has attracted considerable attention, surprisingly few studies have tested its proposed benefits under tightly controlled laboratory conditions. Much of the discussion around dynamic lighting, or Human Centric Lighting (HCL), rests on plausible biological principles, field observations, or experiments that examine light at only one particular time of day. Our study, “Changing color and intensity of LED lighting across the day impacts on circadian melatonin rhythms and sleep in healthy men,” published in 2021, was designed to address this gap. It tested an HCL concept across an entire waking day and compared it with conventional, unchanging office-style lighting (Stefani et al., 2021).

The underlying idea was simple. Natural daylight is never static: it changes in brightness, spectrum, direction, and character from morning to evening. Electric lighting, by contrast, often remains almost unchanged for hours. In our study, we asked whether an indoor lighting system that gradually changed in brightness and color temperature could better support the body’s daily rhythm, particularly the evening rise in melatonin and the transition into sleep.

A controlled laboratory study shows that gradually dimming and warming indoor lighting toward bedtime better preserves the body’s natural melatonin rhythm than constant office lighting.

The Biology Behind Human Centric Lighting

Understanding circadian photoreception

Why Light Matters Beyond Vision

Light enables vision, but that is only part of its biological role. It also influences processes that are not primarily concerned with visually forming images. These are often described as the non-visual effects of light or non-image forming effects of light.

Special light-sensitive cells in the retina contribute to these effects. Known as intrinsically photosensitive retinal ganglion cells, or ipRGCs, they contain the photopigment melanopsin and send information about environmental light to several areas of the brain. One important destination is the suprachiasmatic nucleus, often described as the body’s central or “master” circadian clock (e.g. Berson et al., 2002; Dijk & Archer, 2009; Hattar et al., 2003; Lucas et al., 2012; Provencio et al., 2000).

This internal clock helps organize many processes across the 24-hour day, including sleep and wakefulness, melatonin secretion, body temperature, hormone production, alertness, mood, and aspects of cognitive performance.

Melanopsin is particularly sensitive to short-wavelength light (Bailes & Lucas, 2013). This does not mean, however, that only visibly blue light matters. Ordinary white light also contains short wavelengths and can stimulate melanopsin strongly, especially when it is bright or has a relatively cool color temperature.

The timing of light exposure is crucial. Bright light and/or blue-enriched white light during the day can strengthen the circadian signal and support alertness (Cajochen, 2007; Cheshmeh Noor et al., 2023; Kompier et al., 2020; Mu et al., 2022; Pachito et al., 2018; Prayag et al., 2019; Siraji et al., 2022; Souman et al., 2018; Vandewalle et al., 2009; Viola et al., 2008; Xiao et al., 2021). Light in the late evening or at night can delay the internal clock and suppress melatonin (for a review see (Brown, 2020; Giménez et al., 2022)). This is why healthy-light recommendations generally point in the same direction: brighter days, dimmer evenings, and dark nights (e.g. (Piper et al., 2026)). Melatonin normally begins to rise in the evening. It signals biological night and helps prepare the body for sleep. Bright light, particularly when it strongly stimulates melanopsin, can reduce or delay this rise (Brown, 2020; Giménez et al., 2022; Lewy, 1983). We therefore asked whether a lighting pattern that became progressively dimmer and warmer toward bedtime would allow melatonin to increase more naturally and help people fall asleep more quickly.

Testing Dynamic Lighting Under Controlled Conditions

Study design and protocol

Lighting Conditions

In our 2021 study, a conventional, constant office-like light setting was compared with a system that changed gradually over the waking day. The static condition remained close to 4000 K and delivered about 70 lx melanopic equivalent daylight illuminance (mEDI) at the eye (Figure 1, green line).

Under dynamic lighting, brightness and color temperature rose after waking, remained somewhat higher and cooler during the middle of the day (around 5000 K), and then declined progressively. Near bedtime, the room was warm and very dim, with less than 1 lx mEDI at the eye (Figure 1, red line).

The system did not reproduce daylight in all its complexity. Its main purpose was to create a gradual transition from daytime lighting to an artificial dusk, rather than keeping the room equally bright until a sudden lights-off.

Study Participants

Fourteen healthy men, averaging about 26 years of age, were included in our final analysis. Screening excluded relevant sleep, psychiatric, visual, and color-vision disorders as well as extreme chronotypes.

Before each laboratory visit, participants maintained a regular sleep schedule for one week, verified with sleep diaries and wrist actimetry. Recent shift work, trans meridian travel, smoking, and relevant drug or medication use were exclusion criteria.

Experimental Design

Each participant completed both lighting conditions in separate laboratory stays, with the order balanced across the group and about one week between sessions.

Each stay lasted 49 hours in rooms where light, temperature, humidity, and noise were controlled and ordinary time cues were removed. The schedule was aligned with each participant's habitual sleep timing.

After a common baseline evening and an eight-hour sleep opportunity, participants spent a 16-hour waking day under one of the two lighting conditions. A second eight-hour sleep period and a final waking interval followed under controlled conditions.

Outcome Measures

Saliva samples were used to track melatonin across the day, including its evening onset and the total amount present during the final 4.5 hours before bedtime.

Sleep was assessed with polysomnography, allowing us to examine sleep onset, sleep stages, and EEG delta activity. Participants also completed repeated ratings of sleepiness, vigilance, concentration, and visual comfort, together with tests of sustained attention and working memory.

The Results

Key experimental findings

A Stronger Evening Melatonin Rise

The clearest physiological difference concerned evening melatonin. Under both lighting conditions, melatonin followed its expected daily rhythm: levels were low during the day and rose toward the evening. Yet the rise before bedtime was more strongly attenuated under static lighting.

During the treatment evening, the average melatonin AUC in the 4.5 hours before

bedtime was approximately 5.54 pg/ml*h under static light and 9.47 pg/ml*h under dynamic light. This indicates that the constant 4000 K lighting reduced the natural evening melatonin rise more strongly than the dynamic condition.

The difference becomes easier to understand when looking at the light reaching the eye shortly before sleep. Ten minutes before bedtime, the mEDI was around 70 lx under static light but only 0.42 lx under dynamic light. One hour before bedtime, melanopic EDI under dynamic lighting was about 4.5 lx.

In practical terms, the participants in the dynamic condition spent the late evening under much less melanopically effective light. The lighting environment therefore gave the body a clearer signal that night was approaching.

Melatonin Onset Was Better Preserved

We also examined when melatonin began to rise. In the static condition, melatonin onset occurred significantly later on the treatment evening than on the baseline evening, with an average delay of about 54 minutes. In the dynamic condition, there was no comparable delay.

This suggests that constant 4000 K neutral-white light extending into the late evening may push the beginning of biological night to a later time, whereas the dynamic condition appeared to protect against this shift. The result should nevertheless be interpreted carefully, because the overall main effect of lighting condition on melatonin onset was not significant. The important

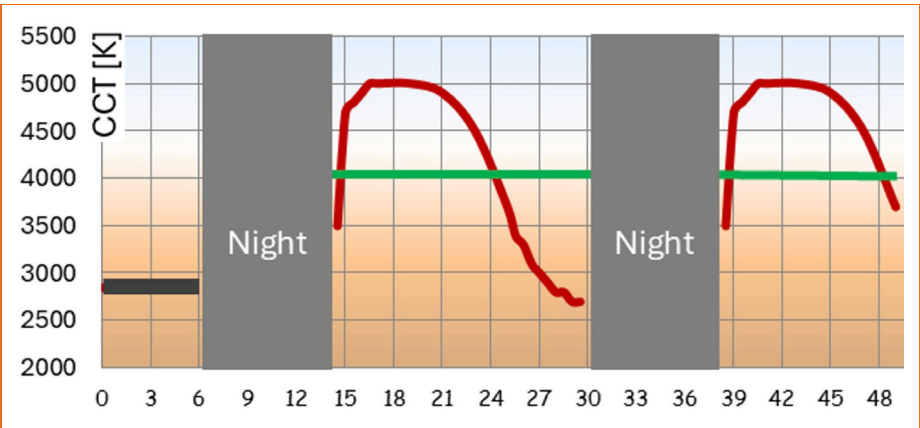


Figure 1: Change of color temperature during the study. Before the first night (the baseline night) participants spent the evening under 2,700 K fluorescent lighting.

observation was the different change from baseline to treatment under the two lighting conditions.

Participants Fell Asleep Faster

Participants entered sleep a few minutes sooner after dynamic light: about 7 versus 11 minutes to N1 and 13.7 versus 17.4 minutes to N2. Both differences were statistically significant. The absolute difference was only a few minutes, but the pattern was consistent: after the dynamic condition, participants entered sleep more quickly.

Sleep Architecture Remained Largely Unchanged

Although participants fell asleep faster after dynamic light, the structure of sleep during the night did not differ substantially between the two conditions. We found no significant differences in the amount of N1, N2, N3, REM sleep, or total non-REM sleep. EEG delta activity also showed no clear overall difference.

Alertness, Cognition, and Comfort

One hour before bedtime, participants reported feeling less vigilant under dynamic light than under static light, and they rated the dynamic condition as too dark at that time.

This is understandable. The system was deliberately reducing light exposure in preparation for sleep. A lighting environment that supports biological night may not simultaneously support maximum alertness. Here, the study reveals an important trade-off. Late-evening light can be designed either to sustain alertness and continued work or to support the transition toward sleep. It cannot necessarily maximize both at once.

The lower evening vigilance should therefore not automatically be regarded as a harmful effect. When bedtime is approaching, feeling less activated may be appropriate. On the other hand, this type of setting may be unsuitable for people who need to remain highly alert late in the evening. The result also shows that biologically supportive lighting must remain practical: a light level may be low enough to reduce circadian stimulation but still feel uncomfortably dim.

No Measurable Daytime Performance Advantage

Despite the late-evening difference in vigilance, overall subjective sleepiness did not differ significantly between the lighting conditions. In both conditions, participants showed the expected pattern of lower sleepiness during the day and greater sleepiness in the early morning and late evening.

We had also expected the brighter and cooler daytime part of the dynamic condition to improve attention or working memory. This did not occur. Performance on the psychomotor vigilance task was similar under static and dynamic light, with no significant differences in reaction times or attentional lapses. Performance on the n-back task also did not differ between the two conditions.

There are several possible explanations. First, the daytime difference in melanopic light exposure was small: the dynamic condition provided only about 10% more mEDI (+7 lx) during part of the day. Second, the participants were young, healthy, well rested, and already performing at a high level. This creates a possible ceiling effect, leaving little room for the light to improve performance further. Third, alerting effects of light are often more apparent under stronger exposures, during sleep deprivation, at night, or when people are already sleepy.

Visual Comfort Was Comparable

Overall visual comfort was similar. The main exception was the late-evening setting, when the dynamic light was often judged too dim.

There was also a non-significant tendency for the color of the dynamic lighting to be rated more positively. The daytime change from about 4000 K to 5000 K may have been too subtle to be consciously noticed, particularly because gradual changes are easily masked by visual adaptation.

A practical finding is that the continuous transitions in color and brightness were generally tolerated well. The system was not experienced as broadly disturbing, even though the final evening setting was sometimes judged too dark.

Discussion

Interpreting the findings

Overall Findings

The study's clearest message is that the evening light transition mattered. Compared with constant 4000 K lighting, a gradual reduction in brightness and melanopic stimulation preserved more of the evening melatonin rise and was followed by slightly faster sleep onset.

The effects were specific rather than universal: the intervention did not improve sleep architecture, daytime cognition, general sleepiness, or overall visual comfort.

Important Limitations

The study had several limitations. Only 14 participants were analyzed, and all were healthy young men. The findings cannot automatically be transferred to women, older adults, children, shift workers, or people with insomnia or other health conditions.

Brightness and color temperature changed together. We therefore cannot determine whether the effects were driven mainly by lower illuminance, warmer light, reduced melanopic stimulation, the gradual transition, or the combination of these factors.

The dynamic condition was also not a true reproduction of daylight. Real daylight changes not only in intensity and spectrum but also in direction, spatial distribution and starts and ends with the blue hour. The experimental system is better described as biologically inspired electric lighting than as daylight simulation.

Finally, the evening became extremely dim. This may be advantageous biologically but impractical for many real-world activities. Reading, cooking, cleaning, moving safely, or working may require more light. Good lighting design must therefore balance visual needs with biological aims.

Laboratory conditions also differ from everyday life. Real environments include daylight through windows, screens, televisions, street lighting, and light from neighboring rooms. People move, change their gaze direction, and spend time in different spaces. The effects of a dynamic ceiling-light system in homes or workplaces may therefore be smaller or more variable than under laboratory conditions.

Implications for Lighting Design

The study does not imply that every office needs a complex dynamic lighting system. It does, however, support the broader principle that indoor light should change with the time of day. During the day, people generally benefit from sufficiently bright light, preferably including daylight. During the final hours before sleep, it is sensible to reduce light intensity at the eye, avoid unnecessarily high melanopic stimulation, and limit cool-white overhead lighting.

A gradual transition may be more biologically appropriate than keeping a room brightly lit until bedtime and then abruptly switching the lights off. In private homes or nursing-care facilities, this can be achieved with dimmable lighting, warmer light sources, lower general room brightness in the late evening, and local task lighting only where it is needed.

Putting the Findings into Context

The clearest effects in this experiment concerned evening melatonin and sleep onset. Dynamic lighting that became progressively dimmer and warmer toward bedtime reduced melatonin attenuation and helped participants fall asleep faster. However, the study should not be regarded as a complete test of the full potential of Human Centric Lighting.

The daytime contrast between the two conditions was comparatively small. The dynamic condition reached only about 76 lx melanopic EDI, well below the 250 lx melanopic EDI recommended by Brown et al. for daytime exposure at the eye (Brown et al., 2022). It is therefore possible that the light stimulus was simply too modest to produce measurable differences in alertness or cognitive performance in young, well-rested participants who were already performing at a high level. This null finding should not be interpreted as evidence that stronger daytime light is ineffective. Reviews and meta-analyses suggest that brighter daytime light can support alertness and aspects of cognition, although the effects vary with the task, timing, exposure conditions, prior light history, and individual characteristics.

This broader interpretation is consistent with the consensus statements of the “Light for Public Health” initiative, which emphasize that bright daytime light can support alertness and cognitive performance under some conditions, whereas evening and nighttime light can delay circadian timing and disturb sleep. They also stress that responses depend on intensity, spectrum, timing, duration, prior light exposure, and individual context. (<https://lightforpublichealth.org/>). The recent public-health policy brief “Bright days, dark nights” expresses the same principle in deliberately simple terms: brighter light in the morning and daytime, lower light in the evening, and darkness or near-darkness during sleep (Piper et al., 2026).

The Swiss guidance on dynamic lighting in residential and nursing-care facilities offers a practical example of how these principles can be translated into real environments (<https://dynamischeslicht.ch/>). It treats dynamic lighting not merely as a change in correlated color temperature, but as part of a complete daily light-dark rhythm: sufficiently bright days, gradual reductions toward evening, and protected darkness at night.

Conclusions

Overall take-home message

The study shows that gradually reducing indoor light intensity and melanopic stimulation toward bedtime can better preserve the evening melatonin rise and modestly shorten sleep onset compared with constant office-style lighting. However, the intervention did not produce measurable improvements in sleep architecture, daytime cognition, general sleepiness, or overall visual comfort.

Seen in a wider context, the value of bright daytime light extends beyond possible short-term gains in performance. Together with dim evenings and dark nights, it creates the strong and regular daily light-dark contrast that lies at the heart of good circadian light hygiene and supports circadian organization, sleep, and broader health (Gubin et al., 2025). ■



The foundation of good circadian light hygiene: Bright days. Dim evenings. Dark nights. (c) LEDprofessional.

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Before joining HSLU, he worked as a postdoctoral researcher at the Centre for Chronobiology at the University Psychiatric Clinics Basel (UPK Basel), where he contributed to experimental studies on light exposure, circadian regulation, and melatonin dynamics. At HSLU, he conducts applied and translational research at the intersection of radiometry and photobiology, focusing on the development and evaluation of innovative lighting concepts and light dosimeters that harmonize visual and non-visual effects of light.

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Intermittent Light Exposures in Humans: A Case for Dual Entrainment in the Treatment of Alzheimer's Disease

Mariana G. Figueiro^{1,2,*} and Sagan Leggett^{2,3}

Circadian sleep disorders are common among American adults and can become especially acute among older adults, especially those living with Alzheimer's disease (AD) and mild cognitive impairment (MCI), leading to the exacerbation of symptoms and contributing to the development and advancement of the diseases. This review explores the connections between circadian sleep disorders, cognition, and neurodegenerative disease, offering insights on rapidly developing therapeutic interventions employing intermittent light stimuli for improving sleep and cognition in persons with AD and MCI. Light therapy has the potential to affect sleep and cognition via at least two pathways: (1) a regular and robust light-dark pattern reaching the retina that promotes circadian phase shifting, which can promote entrainment and (2) 40 Hz flickering light that promotes gamma-wave entrainment. While this is a new area of research, preliminary evidence shows the potential of dual circadian and gamma-wave entrainment as an important therapy not only for those with AD, but also for others with cognitive impairment.

Introduction

Forty-five percent of Americans report sleep problems that affect their daily activities at least once per week, with 35% reporting poor or fair sleep quality and 20% reporting that they did not feel refreshed by sleep on any day of the past week [1,2]. Asynchrony between normal work and social schedules and the timing of the internal clock [3] can lead to sleep disorders and sleep deprivation, particularly if the asynchrony is prolonged for an extended period, which in turn can negatively affect task performance, cognition, and general health [4–6]. Sleep disorders and their attendant decrements can become especially acute among older adults, especially those living with Alzheimer's disease (AD) and mild cognitive impairment (MCI), leading to the exacerbation of symptoms and contributing to the development and advancement of the diseases [7–9]. In fact, of the estimated 5.8 million people in the United States living with AD and related dementias (ADRD) [10], at least one-third experience difficulty sleeping [11,12] and approximately two-thirds of their estimated 18.5 million unpaid caregivers report sleep disturbances themselves [10,13,14].

This review explores the connections between circadian sleep disorders, cognition, and neurodegenerative disease, offering insights on rapidly developing therapeutic interventions employing entraining light stimuli (both continuous and intermittent) for the treatment of sleep disorders, including in those with AD and MCI. Light therapy has the potential to affect sleep and cognition via at least two pathways: [1] a regular and robust light-dark pattern reaching the retina that promotes circadian phase shifting and thus, entrainment and [2] 40 Hz flickering light that promotes gamma wave entrainment. Both are discussed below.

Circadian Rhythms

Circadian rhythms are endogenously driven biological rhythms that have a period close to 24 hours (h) and that can be entrained by exogenous time cues. Circadian rhythms are generated and regulated by a biological clock located in the suprachiasmatic nuclei (SCN) in the hypothalamus in the brain. In the absence of external cues, these rhythms free-run with a period close to, but not exactly 24 h [15]. In humans, circadian rhythms free-run with an average period of 24.2 h. Light-dark patterns reaching the retina are the major synchronizers of circadian rhythms to the local position on earth and to the 24-h solar day, a process referred to as entrainment [16].

Given that the circadian system in humans free-runs with a period slightly longer than 24 h, the human circadian system needs to receive light after minimum core body temperature (usually in the morning hours) to maintain daily entrainment. This is because morning light will advance the timing of the clock while evening light (prior to minimum core body temperature) will delay the timing of the clock. It should be noted, however, that in general, entrainment is assessed in controlled laboratory conditions, while the studies performed in the field measure phase shifting, such as phase advance or phase delay using downstream outcome measures, such as sleep-wake cycle.

As befits a diurnal species, the human biological clock interacts with the sleep-wake cycle to maintain waking during the day and sleep at night. The sleep-wake cycle is regulated by two systems, the circadian system and the homeostatic system [17,18]. Sleep consolidation and quality are reported to be best when the circadian and homeostatic systems are aligned [19]. With greater time awake, homeo-

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static mechanisms increase sleep pressure as bedtime approaches. The circadian system sends an alerting signal to the body to counteract sleep pressure during the day and a sleeping signal during the night, promoting a consolidated night of sleep.

Sleep, Brain Activity, and Brain Pathology

Studies have shown that non-rapid eye movement (NREM) sleep, rapid-eye movement (REM) sleep, and slow oscillations (SOs, 0.3–1 Hz, detected in the cerebral cortex during NREM sleep, when neuronal activity is synchronized.) are associated with improvement in cognition [20], attention [21], and memory [22]. Specifically, an increase in NREM sleep has been associated with improved long-term memory formation [23] and SOs have been shown to be independently associated with improved cognitive performance [24–28].

With respect to AD, sleep disturbance has been investigated as both a symptom of and a risk factor for the disease [6,29,30]. Research has shown a correlation between sleep disruption and subjective cognitive decline, before MCI or AD manifest [31]; less sleep fragmentation has been linked to lower risk for AD in older adults [32]; and treating apnea-related sleep disturbance can delay the onset of MCI [33]. Research relates sleep problems with AD pathology ($A\beta$ and tau), showing a bidirectional relationship between sleep disruption and $A\beta$ and tau accumulation in rodents and drosophila [29,34–37]. Consistently, increasing cortical $A\beta$ accumulation is also associated with sleep fragmentation [34,35]. Poor sleep correlates with $A\beta$ and tau pathology severity among people with AD and MCI [38–42], and recent studies indicate associations between AD pathology and NREM sleep [40,43]. Recently, Fultz et al. [44] simultaneously measured functional magnetic resonance imaging (fMRI) studies measuring blood-oxygenation-level-dependent (BOLD) signals, electroencephalogram (EEG) and cerebrospinal fluid (CSF) and observed that at 0.05 Hz (SO that occurs during NREM sleep), there was a large-amplitude pulsatile flow of CSF.

Given that the glymphatic system has been shown to clear $A\beta$ during sleep [37], along with the corollary that sleep disturbance permits the accumulation of $A\beta$, it is reasonable to conclude that techniques for improving sleep could be employed to counteract $A\beta$ accumulation, and thus, memory decline and progression from MCI to AD.

Gamma Band Oscillations and Brain Health

Gamma activity is composed of rhythmic oscillations that reflect underlying neural synchronizations. Although there is no agreed-upon frequency band that corresponds to gamma oscillations, the accepted lower and upper limits are usually in the range of 20–30 Hz and 80–120 Hz, respectively.

For the most part, gamma oscillations reflect the excitatory and inhibitory activity of interneurons. The cycle starts when excitatory neurons fire, triggering a synchronized discharge of inhibitory interneurons that impede the original excitatory neurons, briefly silencing them. The cycle restarts when the inhibitory signal wears off and allows the excitatory neurons to resume firing [45]. Gamma oscillations can be observed throughout the cerebral cortex and correspond to the activation of the cerebral cortex. In the sensory cortex, gamma oscillations can be modulated by presence of sensory stimulation. For example, rhythmic visual stimuli at a certain frequency (i.e., flickering light) will elicit a brain response in synchrony with the frequency of those stimuli. In the visual cortex, exposure to visual stimuli (e.g., light bars) increases power in the 35–50 Hz range [46]. In their study with cats, Gray and Singer showed that the probability of neurons to fire in response to the presentation of optimally aligned light bars within their receptive field is greater when the stimulus has a peak frequency near 40 Hz. They also observed that this was a cortical response (i.e., a response of local neurons in the visual cortex) rather than a thalamic response.

Gamma-band oscillations have been associated with attention, working memory, and associative learning [47]. During information-processing events, gamma oscillations allow for selective transmission of sensory information across distributed neurocircuits. Enhanced gamma activity is associated with the enhanced coherence between brain areas [48–51]. For example, working memory processes have been associated with the coupling between the phase of theta (4–8 Hz) and the amplitude of gamma [52]. In fact, Tort et al. [53] demonstrated that theta–gamma coupling strength directly correlates with increased performance during learning sessions in rats, suggesting theta–gamma coupling plays a role in memory recall [53].

Interestingly, human AD patients [54–56] and AD mouse models [57–59] show reduced power of oscillatory activity in the gamma range (30–100 Hz), which mediates

essential neural functions including cortical arousal, sensory processing, working memory, attention-dependent stimuli, and higher order cognition [60–64]. This deficit provides a valuable avenue to explore potential treatments for humans with AD or other cognitive impairments.

Therapeutic Lighting Techniques

Light for Entrainment and Phase Shifting of the Circadian System

It is well known that the light-dark cycle is the primary stimulus for synchronizing the circadian system, whose rhythms (e.g., the sleep-wake cycle) repeat approximately every 24 h. Ideally, light of the appropriate amount, spectrum, distribution, duration, and timing synchronizes the internal human circadian clock with solar day-night cycle to help maintain synchrony with work demand times [65]. In humans, this synchronization occurs when the circadian system phase advances daily and outcome measures are generally downstream measures.

Lighting characteristics affecting the circadian system, as measured by acute melatonin suppression and phase shifting of dim light melatonin onset (DLMO), a marker of the timing of the biological clock, differ from those affecting our ability to read black font on a white paper. While less light than was originally demonstrated in the 1980s is needed to suppress nocturnal melatonin production, significantly higher amounts of light are needed to affect melatonin than those needed to activate the human visual system [66,67]. Indoor daytime workers, however, may spend their days in “biological darkness” because typical exposures to electrical lighting in indoor environments can be insufficient for entraining the circadian system [68]. The lack of a strong light-dark stimulus to the circadian system can lead to sleep disturbances, such as those experienced by older adults, including AD patients, living in more controlled environments. Indeed, it has been shown that middle-aged adults receive approximately 58 min of bright light per day [69] while older adults in assisted-living facilities receive bright light for only 35 min per day [70]. Adults in nursing homes see as little as 2 min per day.

Following the discovery of the intrinsically photosensitive retinal ganglion cell (ipRGC), a series of animal-model studies showed that circadian phase shifting can occur via input from the ipRGCs and/or the rods and cones, either alone or in combination [71,72]. These studies clearly suggest that,

although the ipRGCs are instrumental to transduce the signal from the retina to the SCN [73,74], melanopsin alone, the opsin that provides the ipRGCs with its intrinsic photosensitivity, is not needed for circadian phase shifting, and neither are rods and cones alone [74].

The peak spectral sensitivity for acute melatonin suppression and phase shifting of DLMO is close to 460 nanometers (nm) [75–77]. Timing of exposure is also important for affecting the biological clock. The same stimulus presented in the morning—or after the minimum core body temperature, CBT_{min} , that typically occurs in the second half of the night—will advance the timing of the clock in the following cycle (i.e., bedtimes and waketimes will be earlier the following day). Light given in the evening and early part of the night (before CBT_{min}) will delay bedtimes and waketimes [78].

The duration of light exposure required for melatonin suppression depends on the light stimulus's magnitude [79]. Continuous exposure to $74 \mu\text{Wcm}^{-2}$ of a narrowband, short-wavelength light stimulus (peak close to 470 nm), for example, will elicit measurable melatonin suppression after 5–10 min. Continuous exposure to $2 \mu\text{Wcm}^{-2}$ of the same blue light source, on the other hand, will elicit measurable melatonin suppression only after 90 min [79]. Consistently, a 12-min exposure to 4100 K fluorescent light ($> 6000 \text{ lx}$ at the cornea) more effectively phase-shifts circadian rhythms than exposures to lower light levels for longer durations (e.g., 6.4 h), as demonstrated by Chang et al. [80].

Finally, research shows that it is important to accurately measure light exposures over the 24-h day, as opposed to just taking a “snapshot” measurement of light exposure at one certain place and time [81,82]. Given that the circadian system appears to keep track of light exposure, knowing an individual's light exposure history over the past 24 h can help determine the best light prescription for the next 24 h [83]. Therefore, a light treatment designed to promote earlier bedtimes should not be limited to reduced exposure to blue light in the morning but should instead control the total circadian light exposure during waking hours.

Amid ongoing investigation into the retinal mechanisms involved in photic stimulation of the circadian system, Rea et al. [77,84] have proposed and continued to develop a model of human circadian phototransduction that is consistent with known retinal neuroanatomy and neurophysiology [85]. The human circadian phototrans-

duction model is based on the response of the ipRGCs [86], but it also includes responses from rods and cones, which have also been shown to provide input to the ipRGCs [71,72]. The ipRGCs, through the retinohypothalamic tract (RHT), transduce the combined photic signal to the master pacemaker, located in the suprachiasmatic nuclei (SCN). According to the Rea et al. model [77,85], the cones provide indirect input to the SCN via synapses in the retina, one of which includes the spectrally opponent (blue versus yellow) S-cone bipolar neurons that combine input from all three cone types to provide depolarizing-only (S-ON) input to the ipRGCs. The ipRGCs convey the combined photic information to the SCN. Following the model, while the intrinsically photosensitive response from the ipRGCs combines its signal with depolarizing “blue” response from the S-ON bipolar, the hyperpolarizing “yellow” response will not be received by the ipRGCs. In the case of light spectra that evoke a “yellow” response from the S-ON bipolar, the ipRGCs' response alone determines the photic information conveyed to the SCN.

Continuous Light for Circadian Phase Shifting and Entrainment

Light therapy for improving sleep, mood, and behavior in AD patients has been the subject of investigation since the 1990s. A comprehensive review of the impact of light on circadian phase shifting and thus, entrainment has been published elsewhere [87], but a summary of some of these studies is presented below.

One of the first studies showing the positive impact of light on circadian rhythms of AD patients was published by van Someren et al. [88]. They studied the effects of increased levels of bright light during the day on 22 institutionalized older adults with severe AD. Ambient, unattended high light levels ($> 1000 \text{ lux}$ at the eye) delivered from ceiling luminaires and windows were used to deliver the intervention in spaces where most of the patients stayed during the day. The results showed that 4 weeks of bright light exposure over the course of a day improved disturbed circadian activity/rest rhythms in older adults with severe dementia.

Yamadera et al. [89] evaluated the effect of bright light exposure (3000 lux for 2 h each morning) on cognitive functions and circadian rhythms in individuals with AD. The 27 participants experienced the intervention over four consecutive weeks. There was also a significant decrease in daytime napping, awakenings during sleep, and overall percentage of time of sleep increased for

all participants. The authors speculated that the bright light exposure improved circadian rhythms and cognitive functions for participants in the early stages of the disease.

Not all of the studies, however, showed positive impacts of light therapy on sleep. Dowling et al. [90] investigated the effect of 1 h of bright light ($\geq 2500 \text{ lux}$) in the morning for 10 consecutive weeks on nighttime sleep, wake time during the day, and circadian rhythms in a study of 46 AD patients. No significant changes were observed in sleep efficiency, sleep time, wake time, or number of awakenings between the control group and the intervention group. However, the authors noted that the greatest improvements in the activity/rest rhythms occurred in those who experienced their 10 most active hours during typical hours of sleep at baseline.

In terms of long-term light therapy, Riemersma-van der Lek et al. [91] were the first to investigate the effect of long-term (maximum of 3.5 years) light exposure and oral melatonin in a study of 189 AD patients. Ceiling-mounted fixtures with fluorescent tubes were installed in a common living room. Results showed the light exposure attenuated cognitive decline, ameliorated depressive symptoms, and attenuated the increase in functional limitations by over half. Melatonin increased negative mood and withdrawn behavior, but shortened sleep latency and increased sleep duration.

Although studies to date have shown that light can be a powerful therapy for mitigating sleep disturbances and increasing memory consolidation in older adults with AD, not all of the studies showed consistent positive results [92,93]. This lack of consistency in the results is likely due to the fact that most of the studies to date lack a formal specification of the stimulus. The amount, spectrum, timing, distribution, and duration of the light exposures are not always described in the studies, and in many cases, not even taken into account when delivering the intervention in the field. In fact, a 2014 Cochrane review [94] of eight studies found insufficient evidence to recommend the use of light therapy for improving sleep and behavior in AD patients. The reviewed studies included different lighting interventions, however, and none of them controlled or measured the actual light dose that participants received during the interventions [94]. The lack of control for the light delivery methods may have affected the outcomes of the analyses.

With the goal of addressing the issue of lack of control of the stimulus delivery and

measurement, Figueiro and colleagues developed a tailored lighting intervention (TLI) designed to effectively affect circadian phase, and, thus, promote entrainment of the circadian system. Although circadian entrainment was not directly measured in the field, it was operationally defined that better circadian entrainment was associated with better sleep, mood and behavior. Figueiro and colleagues used the Rea et al. model to develop the TLI, which was used to deliver a robust light-dark pattern to persons with AD living at home [95] and in more controlled environments [96–98]. In their studies, circadian-effective light was delivered from waking to 6 p.m. and circadian ineffective light was delivered during evening hours. Treatment duration varied from 4 weeks to 6 months. Results showed that the lighting intervention significantly reduced subjective sleep disturbances, increased objective sleep measures, and improved behavior, as observed by a reduction in depression and agitation scores [98]. These findings were consistent with earlier studies showing that all-day or morning light exposures for short (4 weeks) and long (3.5 years) periods consolidated activity/rest patterns and improved subjective measures of depression [88,91,92,99].

Intermittent Light for Circadian Phase Shifting and Entrainment

In an experiment by Zeitzer et al. [100], 2-ms light pulses presented to the open eyes of six subjects every 1 min for a duration of 60 min during the early part of the night shifted (delayed) circadian phase by an average of 45 min, based on DLMO measurements. They also observed improvements in objective (electroencephalography) and subjective (Stanford Sleepiness Scale) measures of alertness. Although there was a significant phase shift of DLMO, the 2-ms light pulse intervention did not significantly reduce melatonin concentrations in the intervention night compared to the dark control night. While this was the first study showing the impact of pulsed light intervention in humans, its impact on animal circadian phase had been demonstrated before [101,102].

At first, these findings appear to contradict predictions from models of human circadian phototransduction and the circadian pacemaker's response to light [103,104], and suggest that melatonin suppression and phase shifting do not exhibit similar spectral and absolute sensitivities to light [67,80,105]. Indeed, until the above-cited publication by Zeitzer et al. [100], most studies usually showed that prolonged exposure to light stimuli (i.e., longer than several milliseconds) would reliably phase

shift DLMO and acutely suppress melatonin [79,80].

The responses of the photoreceptor classes vary widely; cones respond very quickly to light stimuli (< 50 ms) [106] while the ipRGC's response is much slower (> 10 s) [86], and cones display a rapid, heightened response to pulses of bright light that is followed by a slow decay, even after the stimulus is extinguished [107,108]. One hypothesis tested by Figueiro et al. [82] was that, based on this slow decay of cone responses, flashes of bright, short-wavelength light could stimulate the SCN via the depolarizing, S-ON bipolar synapse without necessarily inducing a direct response from the ipRGCs. The Rea et al. model is therefore consistent with the hypothesis that a series of brief, short-wavelength light flashes stimulating the S-cones (a “blue” response) could convey photic information to the SCN. Conversely, a series of brief, longer wavelength green-, yellow-, or red-light flashes (i.e., a “yellow” response) would not elicit a response because it could not circumvent ipRGC sensitivity's high threshold and slow response.

First made possible by determining the human eyelid's spectral transmittance [109], subsequent laboratory research confirmed the efficacy of a light mask worn during sleep that delivered 60 min of continuous green ($\lambda_{max} \approx 527$ nm) light through the closed eyelids of sleeping subjects for suppressing nocturnal melatonin and phase shifting DLMO [110]. In a second publication, Figueiro et al. [82] tested the intermittent light hypothesis by compar-

ing the effectiveness of flashing green and flashing blue lights on phase shifting of DLMO and on acute melatonin suppression in humans. They tested the hypothesis that brief pulses of short-wavelength light (blue) delivered in the early part of the night would delay DLMO and suppress nocturnal melatonin, while similarly delivered longer wavelength (green) light would not elicit the same circadian system responses. Three light-stimulus conditions were delivered to 16 subjects during sleep: [1] 111 Wm^{-2} of blue ($\lambda_{max} \approx 480$ nm) light presented as 2-s flashes at 1-min intervals for 1 h, [2] 131 Wm^{-2} of green ($\lambda_{max} \approx 527$ nm) light presented continuously for 1 h, and [3] the same green light presented as 2-s flashes at 1-min intervals for 1 h. After correcting for mean eyelid transmittance, the corneal irradiance levels of the flashing blue and the flashing and continuous green lights were set to values previously shown to be of approximately equal effectiveness for stimulating the human circadian system over a continuous exposure of 1 h (circadian stimulus or CS = 0.31 for blue and CS = 0.38 for green).

Results showed that, compared to a dark control night and corrected for the natural drift of circadian phase, the flashing blue light evoked a statistically significant phase delay as measured by the incremental change in DLMO (Figure 1) and reliably suppressed melatonin. The flashing green light, conversely, did not reliably shift DLMO compared to the natural drift in phase observed for the dark control, nor did it reliably suppress nocturnal melatonin.

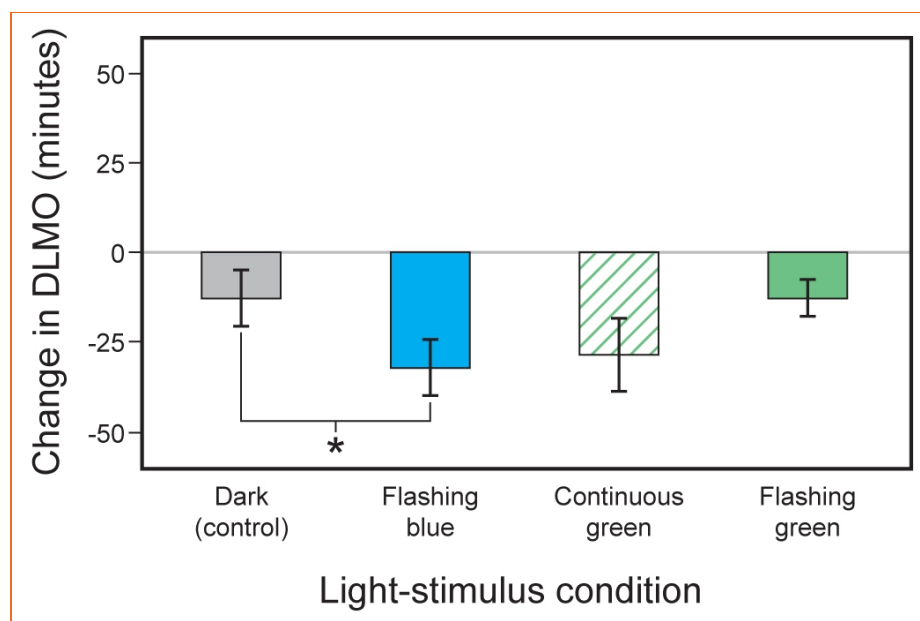


Figure 1: Changes in the timing of DLMO observed for the four light-stimulus conditions employed by Figueiro et al. (82). The error bars represent standard error of the mean. * represents $p = 0.05$.

This study was followed by another study where the impact of the flashing blue lights was tested in a laboratory setting and a follow-up study conducted in the field, where exposures to light outside the intervention were measured using a calibrated personal device, but not controlled [111]. In the laboratory study, they exposed 11 subjects to the flashing blue light delivered to close eyelids for 1 h in the early part of the night. The goal of this laboratory study was to determine the effectiveness of the light to suppress nocturnal melatonin. Melatonin levels during the intervention night, when the flashing lights were energized for 1 h, were significantly reduced compared to the control night, when the mask was worn but not energized. For the field portion of the study, 10 subjects completed a 2-week protocol. During the first week (baseline), they lived their normal lives while wearing light meters and actigraphs. At the end of the week, they came to the laboratory to collect saliva samples for DLMO measurements. During the second week (intervention), light masks delivering flashing blue lights were programmed to turn on 1 h after their bedtimes and remain energized for 2 h, turning off at least 1 h before predicted CBT_{min}; therefore, the intervention was designed to delay their DLMO times. DLMO was significantly delayed ($p = 0.003$) after intervention compared to the control (average delay was 24.5 min), extending the results observed by [82] to field settings.

Following the laboratory and field studies confirming their hypothesis, Figueiro [112] tested the effectiveness of the flashing blue light on delaying the circadian system of those with early sleep onset living in their homes. They recruited 28 subjects (9 early awakening insomniacs) to participate in an 8-week, placebo-controlled, within subjects, crossover study. Two lighting conditions were tested, an active (flashing blue light delivered during early part of the night) and a control (flashing red light also delivered during the early part of the night). For each lighting condition, the subjects collected data during 2 baseline weeks and 1 intervention week. Saliva samples for DLMO measurements were collected at the end of each baseline and intervention week. Actigraphs and a calibrated light meter were used during the entire study.

After 1 week of the lighting intervention, results showed that exposure to the flashing (2-s pulses, every 30 s) blue light for durations ≤ 3 h, starting at least 1 h after bedtime, delayed DLMO by an average of 34 min. A control intervention, delivering a flashing red light ($\lambda_{max} = 640$ nm) exposure of the same timing and duration,

however, delayed DLMO only minimally (6 min). Sleep start times were significantly delayed (by approximately 46 min) at day 7 compared to day 1 after the flashing blue light, and sleep efficiency was not affected by the intervention. Although DLMO and sleep start times were successfully delayed among subjects reporting a history of early awakening insomnia, it remained unknown whether the use of the light mask over longer periods would delay circadian phase and the timing of sleep among those with early sleep onset.

In order to investigate the effectiveness of the flashing light mask in a larger group in real-life conditions, using a crossover, placebo-controlled design, Figueiro et al. [113] exposed 32 subjects to either an active blue ($\lambda_{max} = 480$ nm) lighting intervention or a placebo red ($\lambda_{max} = 640$ nm) control through closed eyelids during sleep. The light stimulus was presented 1 h after bedtime for consecutive 8 weeks. The light was administered via custom-built light masks that delivered a series of 2-s light pulses at 30-s intervals for ≤ 2 h (approximately 240 pulses/night). Subjective measures of sleep and depression (questionnaires) and objective measures of sleep (wrist actigraphy) served as dependent variables. Statistically significant ($p < 0.05$) improvement in seven of the eight subjective sleep measures were reported within both conditions, but no differences were observed between the two conditions. It should be noted that in this long-term study, subjects' daytime light exposures—particularly in the morning, which would have counteracted the effect of the flashing blue light in the evening—were not controlled. The authors hypothesized that if orange-tinted glasses had been worn by subjects in the morning, the impact of the intervention would have been more pronounced.

This method of delivering flashing light through closed eyelids while people sleep (Figure 2) nonetheless holds considerable promise for the clinical correction of circadian misalignment, given that light applied close to the CBT_{min} has been shown to maximally shift the circadian pacemaker's timing [78,114]. The CBT_{min} occurs in the second half of the night, approximately 2 h prior to natural waking. For the success of this application, however, light exposures during wakefulness should be monitored at all times, perhaps aided by smartphone applications that provide timing recommendations for receiving and removing light stimuli. Future studies should examine how effectively such closed-loop systems might phase-shift the biological clock in real-life situations.

The effects of temporally modulated light stimuli that are delivered in the morning during wakefulness on circadian entrainment, rather than on circadian phase shifting, remains unexplored even though, as shown by the studies discussed above, the Rea et al. model [77,85] permits qualitative predictions of the impact of temporally modulated light pulses for stimulating the human circadian system, as measured by acute melatonin suppression and shifting of the DLMO times.

Intermittent Light at 40 Hz for Gamma Power Entrainment

Intermittent light stimuli permits gamma oscillations in the brain to resynchronize with the frequency of a flickering light; therefore, the administration of a visual stimulus flickering at 40 Hz will induce gamma oscillations at exactly 40 Hz [58]. Such resynchronization has been shown to improve both learning and memory skills in a murine model [115]. Because hippocampal gamma oscillations are linked to cognitive function, it is also assumed that these resynchronized oscillations are responsible for the increase in cognitive performance [116]. The research in this area is still new and more work needs to be performed to determine the benefits of 40 Hz flashing lights on cognition.

Recent research has demonstrated that in hippocampal region CA1, as little as 1 h of optogenetic stimulation of parvalbumin (PV) interneurons, which are known to induce gamma oscillations [117,118], could reduce A β peptides levels by approximately 50% in 5XFAD mice [58]. A similar reduction was also observed in the visual cortex after mice were exposed to an external flickering light at 40 Hz. When 1-h stimulation was repeated daily over the course of 7 days, 40 Hz flickering light also reduced plaque pathology in the visual cortex of 6-month-old 5XFAD mice, and exposures of longer duration (i.e., 1 h per day for either 22 days or 42 days) similarly reduced the loss of neuronal and synaptic density. The same stimuli also modified microglia morphology, consistent with increased phagocytic activity responsible for neuronal corpse removal in the brain [58,119]. Long-term (> 6 weeks) daily exposure to 40 Hz flickering lights decreased microglia-mediated inflammation in P301S and CK-p25 mice, improved behavioral performance, and reduced loss of neurons in various parts of the brain [58,120]. This was confirmed by Garza et al. [121], who found that 40 Hz flickering light administered to healthy mice increased the expression of cytokines, which plays a central role in microglial recruitment. In a healthy brain, microglia exercise a protective func-

tion that restrains the accumulation of $A\beta$ and may prevent neurodegeneration [122]. It has been hypothesized that resynchronization of gamma oscillations stimulates recruitment of microglia [58,123], which take part in ridding the central nervous system of undesirable features such as dysfunctional neurons or amyloid plaques [124]. If proven to be viable, harnessing the maintenance role of microglia would

be revolutionary, as it would permit the reduction of plaque accumulation using endogenous processes and thereby avoid the introduction of foreign substances to the body. It should be noted that the protective role of microglia in the brain may be lost in later stages of the disease. As toxic amyloid types accumulate in the brain, tau pathology builds up in stressed or damaged neurons, microglia transform into

a destructive or inflammatory state that destroys synapses, secretes neurotoxic cytokines that harm neurons and may make matters worse by spreading tau pathology [122].

It should also be stressed that this therapeutic approach appears to be effective for removing plaques via microglia activation/recruitment in murine models, but it remains unknown whether these findings will translate well to humans. If beneficial in humans, it will be important to determine at which stages of the disease this microglia activation by gamma entrainment switches from being beneficial to detrimental [122].

The first step to initiate this new line of research will be to show that 40 Hz flickering lights leads to an increase in gamma power in the brain. While we are a long way away from proving the efficacy of this intervention for improving cognition in those diagnosed with MCI and AD, a recent small pilot study by Sahin and Figueiro [125] demonstrated that 11 healthy young adults receiving a 40 Hz flickering red light stimulus induced a significant increase in 40 Hz power as well as an overall increase in low gamma power (30–55 Hz). Red light was used as the intervention stimulus because it does not affect the circadian system. There was also a significant correlation between the increase in 40 Hz power and a reduction in subjective sleepiness, as measured by the Karolinska Sleepiness Scale scores. The intervention did not have a significant impact on short-term performance and subjective sleepiness, as measured by the Karolinska Sleepiness Scale, compared to the dark control. According to the authors, this may have been due to a “ceiling effect”, given that these were normal, healthy young adults. Moving forward, it will be useful to perform similar experiments in those with MCI for a longer period (weeks or months) to determine whether this increase in gamma power resulting from exposure to 40 Hz flickering light can improve cognition and delay transition to AD.

Intermittent Light at 40 Hz: A Case for Dual Entrainment

In the only publication investigating the impact of an intermittent light at 40 Hz on both circadian clock genes and gamma entrainment, Yao et al. [123] compared mRNA levels of clock genes (BMAL1, Per2, and Clock) before and after exposure to 40 Hz flickering light using an AD mouse model (APP/PS1). They showed that 40 Hz flicker increased gamma in the visual cortex, decreased $A\beta$ deposition, and decreased protein expressions of APP and phosphorylated tau in the hippocampus. They also showed that 40 Hz flicker

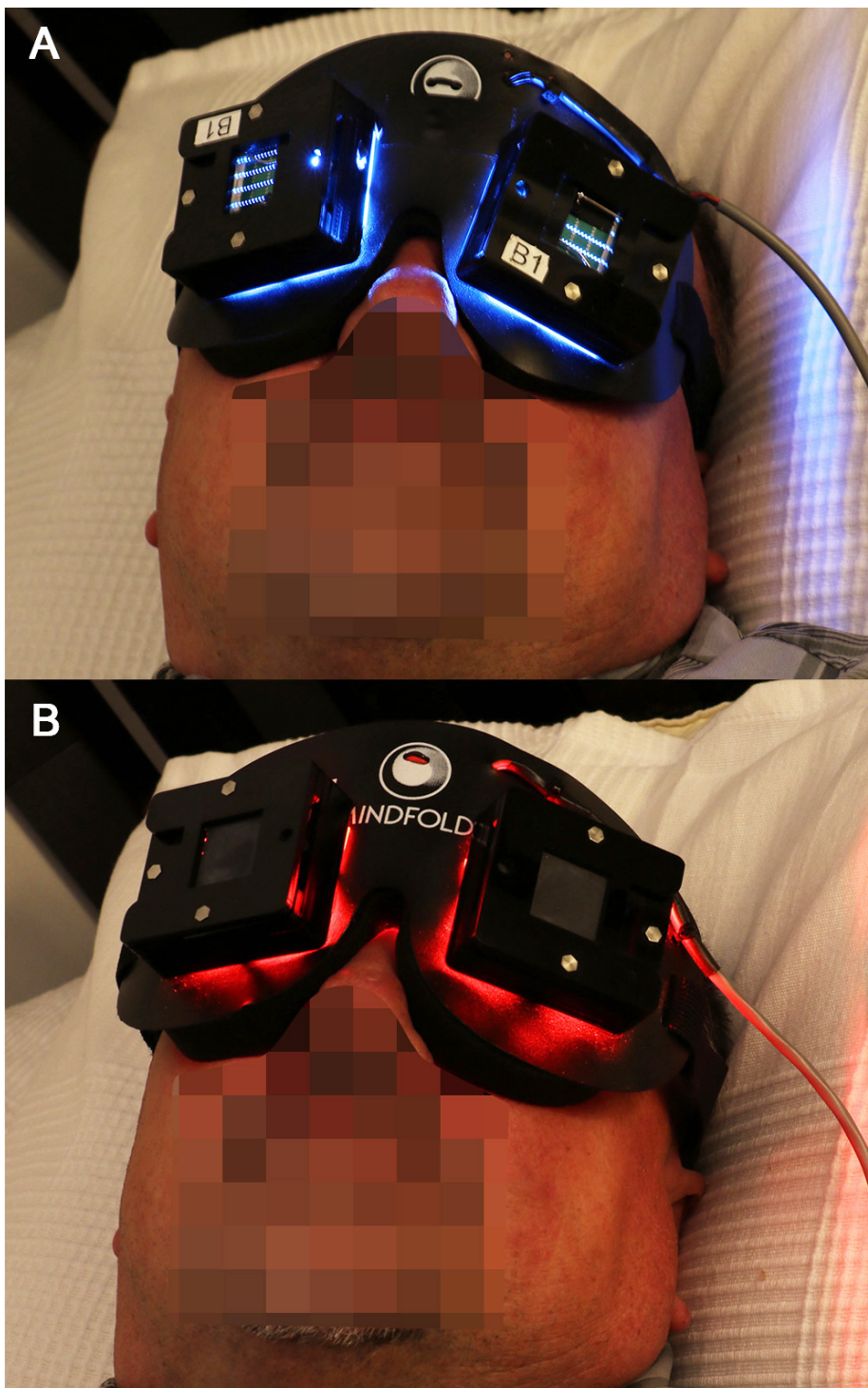


Figure 2: The light mask used to deliver light pulses through closed eyelids during sleep. The light mask contained 2 LED arrays for each eyelid: (A) active blue ($\lambda_{max} = 480$ nm, FWHM = 24 nm) or (B) placebo red ($\lambda_{max} = 640$ nm, FWHM = 25 nm). Written informed consent was obtained from the individual shown in this figure for the publication of this image.

lights partly restored CLOCK, BMAL1, and PER3 gene expression in the APP/PS1 mice, which was shown to be reduced compared to their controls. As noted by the authors, it was not possible from their studies to determine whether it was the light itself or the flicker that drove the observed changes. The wavelength of the light they used for their experiments, 462.8 nm (blue light), is close to the peak sensitivity of the circadian system, thus making it difficult to distinguish the cause of the expression level change. In order to confirm that the restoration of expression levels of genes was due to the flickering light, and not the short-wavelength light, it would be advised to conduct an identical experiment with either a random flicker or with a 40 Hz circadian-ineffective light. Ideally, these studies should be tested in humans and results will help develop new light therapies designed to promote both circadian and gamma entrainment.

Discussion

Light-dark exposures reaching the retina are the major synchronizer of circadian rhythms to the local position on Earth. In general, this synchronization results from small phase advances that occur daily, given that the human circadian clock free-runs with a period slightly longer than 24 h. Therefore, to promote entrainment would be to advance the clock daily. In studies where light stimulus was carefully specified and measured, the effects on sleep, mood, and behavior of various populations, in particular AD patients, were generally positive [95–97]. For the most part, however, light therapy for circadian phase shifting resulting in better entrainment has been continuous, not intermittent. Only a few studies to date have investigated the effectiveness of intermittent light to phase shift the biological clock. This is perhaps due to the limited number of laboratory and field trials as well as to the fact that there is no clear justification for the use of intermittent light for promoting circadian phase shifting and entrainment alone.

One emerging line of research using phototherapy is the use of intermittent light delivering 40 Hz to promote entrainment of gamma oscillations in the brain. This line of research is still in its infancy and unlike with circadian entrainment, dose-response curves to determine optimum light level, spectrum, timing, and duration of exposure have not been developed for gamma entrainment therapy. The efficacy of light or sound alone and the combined use of light and sound therapy to promote gamma entrainment, while promising, is still under

investigation [115,120] and there are limited studies performed in human subjects.

Future research, and perhaps more novel approaches, should investigate the development of a light therapy device that promotes phase shifting of the timing of the clock, and thus, entrainment of circadian rhythms while also promoting entrainment of gamma activity in humans. This would be a good justification for the use of intermittent light to promote circadian entrainment. For that purpose, the use of bright white light or narrow-band short-wavelength (blue) light would be needed, instead of the red light used in the Sahin et al. [125] study. This dual entrainment therapy would likely have additive benefit because it has the potential to improve cognition directly, via entrainment of gamma waves, and indirectly, via improving circadian entrainment and sleep, which in itself is associated with better cognition. One issue that should be considered is the comfort and acceptance of the 40 Hz flickering light and its effectiveness when used in combination with ambient light. Moreover, although the 40 Hz flicker is outside the 0.1–30 Hz flicker range that is better known to induce epileptic seizures, at least one study [126] showed the onset of localized seizures at higher frequencies (60–100 Hz), and therefore, those who are known to suffer from epileptic seizures should not use the flickering lights. It has been suggested that AD patients are more prone to seizures [127], and it is not known whether the flickering lights would have a different effect in those with neurodegenerative diseases compared to healthy people. Nevertheless, intermittent flickering light therapy shows a lot of promise due to its affordable price and easy administration. Initially, testing these interventions in MCI and mild AD patients would likely be the most beneficial, given that this population suffers from *both* sleep disturbances and cognitive deficit.

In summary, this dual entrainment intervention may be very beneficial to those with neurodegenerative diseases. If the same lighting device can be used to target both gamma and circadian entrainment, this could be easily incorporated into the homes of those with early stages of neurodegeneration. While the impact of light for promoting entrainment in those with early and late stages of AD has been shown in the field [95–97], it is yet to be determined whether the flickering light will also have a positive effect in those who are in the early, and more importantly, the later stages of the disease. This is a new area of research, but given that preliminary evidence shows its potential as an important

therapy for those suffering from sleep disturbances or cognitive impairment, future research should investigate the additive effect of these two therapies. ■

Acknowledgements

The research was funded by a NIH Institutional Training Grant (T32 AG057464), the National Institute on Aging (R01 AG034157, R01 AG042602, R01 AG062288), and the Michael Richter Family. The authors acknowledge the editorial and technical assistance of David Pedler, Barbara Plitnick, Levent Sahin, Bridget Bradley, Sharon Lesage, Andrew Bierman, and Mark S. Rea. This open-access article was originally published in *Frontiers in Neurology*, Volume 12 (2021), under the terms of the Creative Commons Attribution License (CC BY).

Conflicts of interest

The authors declare no conflicts of interest.

Keywords: Alzheimer's disease; circadian entrainment; flashing light; gamma entrainment; memory; sleep



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BIO-LOGIC LIGHT - The New Standard for Daylight-like Lighting as a Bridge Between Theory and Practice

Peter Haumer, Product Management at Lumitech

Lumitech and Bartenbach describe a new standard for human-centered lighting design. BLL leads to control curves that combine the natural light requirements of humans and the demands of indoor environments like office, education and health.

The aim of the research project was to develop - based on the current state of scientific knowledge - specifications for biodynamic lighting design using a high-end 3-channel LED technology (CCT: 1.800-16.000 K). These specifications resp. target values primarily include the time-dependent values at the eye for vertical MEDI (daylight equivalent illuminance in lx), color temperatures [K], and spatial light distributions with direct and indirect component.

“Human Centric Lighting” – Terminology

The term Human Centric Lighting – back then it was still abbreviated as HumCL – derives mainly from a study published in autumn 2013 from LightingEurope, ZVEI and A.T. Kearney and is not protected. Therefore, different understandings have been summarized / subsumed under this expression, up to and including potentially abusive appropriation. The full headline of the mentioned study provides more clarity: Human Centric Lighting: Going beyond energy efficiency.

In a professional understanding HCL is by far much more, than merely/simple switching On & Off and Dimming.

There are several definitions: e.g. HCL is biologically effective light. Spoiler: every light-source is more or less biological effective, because every light source has a melanopic action factor - regardless of whether it is stated or not. Much better and more precise: So at least it is about what daylight – meaning the sun and the sky – offers over the course of the day.

In a nutshell: It has to mimic natural daylight – which is a quite challenging task!

This means direct and indirect light components with the required proper CCT-range. One fixed prerequisite for this is also the topic of at least following Planckian Locus. So of course, the goal is to go even beyond e.g. by taking social timing into account and by implementing specific accordingly adapted curves, because sunlight on earth deviates slightly from the ideal Planck curve, primarily due to atmospheric absorption.

Indoor-Society

Why is it so important to pay special attention to artificial lighting conditions with regard to their similarity to daylight?

Several studies show that the average time spent outdoors per day, or the time per day with direct contact to sunlight, is alarmingly low. And this change in behavior occurred mainly only within a few generations, so from an evolutionary point of view, in a very short time. This makes adequate indoor lighting all the more necessary to compensate for this deficiency.

Which Technology Regarding the Light Source is Suitable or Required?

All this leads to the following requirements: In order to optimally support the human biorhythm, it is important that the lighting can imitate the intensity and color temperature of sunlight. Physics tells us, that sunlight on Earth moves approximately along the Planck curve throughout the day. That's the reason why, for evolutionary reasons, artificial light is only perceived as natural light near the Planck curve.

Simple tunable white solutions based on mixing cold and warm white do not meet these requirements. They have a very limited range of color temperatures and are unintentionally located - particularly centrally - far away from the Planck curve. This inevitably results in a severe deviation from Planckian Locus which is inherent to the design.

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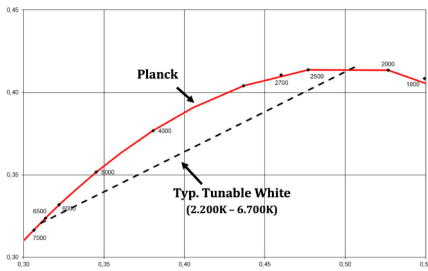


Figure 1: Conventional tunable white solutions based solely on mixing warm and cool white LEDs deviate significantly from the Planckian locus—particularly at mid-range color temperatures—resulting in limited CCT coverage and reduced color quality. © by Lumitech.

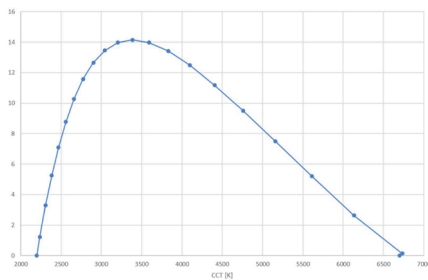


Figure 2: Typical chromaticity deviations exceeding 10 SDCM from the Planckian locus (CIE 1976 u^*v^* UCS), illustrating the limitations of conventional two-channel tunable white systems. © by Lumitech.



Figure 3: 3,500 K light source on the Planckian locus (top) versus a 3,500 K tunable white source with a deviation of >10 SDCM from the Planckian locus (bottom). © Lumitech. Real photographs; no image editing or AI used.

Key message: Tunable white solutions typically only meet Planck's curve at two color points and are therefore far from the Planck curve in the central color temperature range, which leads to a perception that tends to be redder.

This means they do not meet the requirement for perfect daylight white!

Unbeatable advantages of a multi-channel LED solution calibrated along the Planck curve as clearly visible in the photos: Natural color perception (especially improved green perception and non-red-visualizing properties compared to tunable white) All

this results in richer colors, better brilliance, and higher contrast as well as noticeably improved comfort, performance, and concentration.

BIO-LOGIC LIGHT (BLL)

Motivation - with first focus on the demands of modern working and learning environments: Due to social timing/rhythm e.g. like typical office-hours or school-timetables there is a corset independent from season. Therefore, the challenge was to define a daylight-curve that takes social timing into account and is universally applicable during the year and that triggers the circadian-rhythm properly.

Activating, Supportive, and Calming Interventions

Like individual building blocks, so-called interventions combine to form optimized 24-hour control curves that generally follow the natural course of the day. However, interventions are specifically incorporated as targeted measures that improve human well-being or consciously support certain behaviors at a particular time of day. For example, bluer, cooler white light at the beginning of the day facilitates the resetting of the circadian rhythm because the relevant lift is greatest at this time of day. Well-being at midday is addressed by lowering the color temperature slightly beforehand to initiate the rest phase, while afterwards it is raised to mobilize activity.

In the evening, a very warm white light – even after sunset – ensures a relaxed transition into the rest and sleep phase. The sum of various interventions, tailored to the daily routine, results in: light according to BLL criteria.

Human-Centered Implementation of White Light

The Planck curve has so far been the gold standard when it comes to the basis for deciding on the optimal color point of white light. For BIO-LOGIC LIGHT, Bartenbach Research & Development has explored a complementary concept based on perception and focused on optimal white light perception at different color temperatures according to the Judd's curves. It turns out that while human perceptual preference comes very close to the Planck curve, specific slight deviations from it are necessary to achieve a pure white color impression. The result is greater brilliance. This optimizes contrast and makes visual tasks such as reading easier and therefore less tiring. This modified Planck curve forms the basis of the BLL curve and is incorporated accordingly into the lighting designs.

So this means, that In addition BioLogic-Light uses the possibilities of slight, deliberate deviations from Planckian Locus for the sake of improved human white light perception.



Figure 4: 3,000 K @ Planckian locus (top) versus 3,000 K BLL (bottom) with higher contrast and richer color impression. © Lumitech. Real photographs; no image editing or AI used.

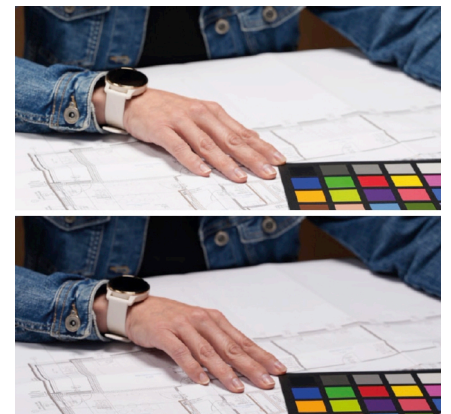


Figure 5: 4,000 K @ Planckian locus (top) versus 4,000 K BLL (bottom) with higher brilliance and richer color impression. © Lumitech. Real photographs; no image editing or AI used.



Figure 6: 6,000 K @ Planckian locus (top) versus 6,000 K BLL (bottom) with better contrast and richer color impression. © Lumitech. Real photographs; no image editing or AI used.

Exemplary Lighting Concepts for Specific Applications

Reference examples can serve as an inspiring starting point for creative lighting planning in individual room environments: BIO-LOGIC LIGHT¹ presents various lighting solutions based e.g. on office lighting planning – including key figures, concept details and photometric variables. They serve as a basis for further planning steps that take additional aspects into account, such as user preferences, spatial concepts, architecture and design requirements.

From exemplary solutions for specific planning - an approach that is also suitable for other industries and applications can be adapted. This allows different planning approaches that can be selected to achieve the required light requirements with the BLL control curves.

Figure 7 shows the example of brightening the surface of the room using wall washers and directional downlights. Alternatively, suspended luminaires with direct lighting can also be used for work surface and indirect light on the ceiling (**Figure 8**).

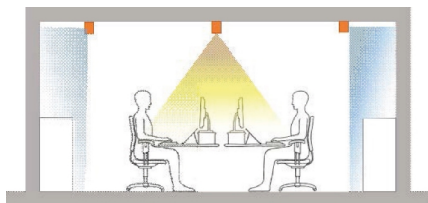


Figure 7: Application example 1: Direct and Wallwash Solution with Downlights for directional task lighting and Wallwashers utilize walls as reflective surfaces to brighten surfaces in the room.

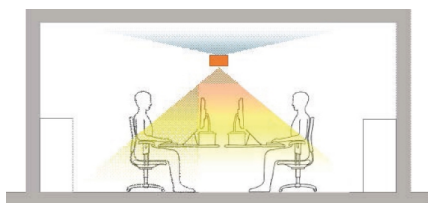


Figure 8: Application example 2: Pendant luminaires or free-standing lamps with two independently controllable light components: i) Directly onto the work surface and ii) Indirectly onto the ceiling (as a reflective surface).

Summary

Everything that has been described can be achieved with the patented high-end 3-channel PI-LED technology, which offers, on the one hand, the necessary extreme wide CCT-range that is needed for direct and indirect ratio and – due to spanning a triangle in the CIE-color-room - the autonomy to move freely within this, which means beyond colors, precise targeted deviations from Black-Body curve.

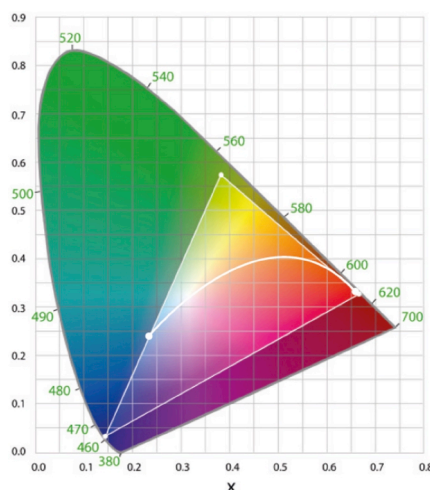


Figure 9: 3-channel PI-LED technology delivers a wide CCT range and accurate color tuning across the CIE color space.

Utilizing the possibilities of a CCT-range of 1,800-16,000K makes it possible, that instead of increasing the intensity, the color temperature of the indirect component is greatly increased (>6500K), and in this way an increase in the MEDl is achieved without an increase in illuminance or light output.

With PI-LED technology, visual demands (visual performance) are partially decoupled from biological demands (melanopic effects). This is achieved by primarily using the indirect light component with cooler color temperatures to meet biological demands, while simultaneously utilizing the direct light component to fulfill visual tasks. In this way, the color temperature in the visual field can be maintained within the comfort range below 5,000 K (preferably 4,300-4,800 K), while the color temperature at the eye is simultaneously increased via the indirect light component to meet biological demands.

As always when we are talking about visible light, there are also more light-quality features necessary and important. Beyond others, it is about color-rendition of the light-source: Ideally, not measured with the outdated and potentially misleading CRI, that only corresponds to some single pastel-shades and deceptive averaging, but based on TM-30.

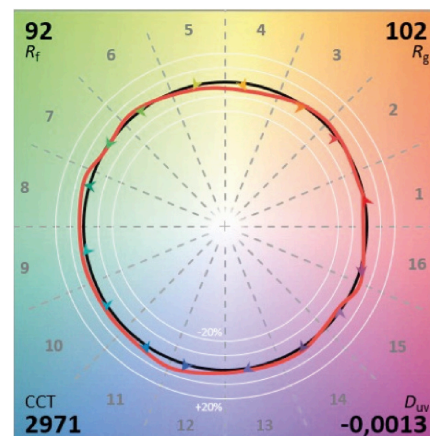


Figure 10: IES TM-30 Color Vector Graphic: Test Source vs. Reference Illuminant (Example: PI-LED Linear System HD).

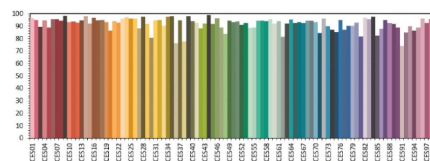


Figure 11: IES TM-30 standardized set of 99 real-world object spectra: CES Color Evaluation Samples (Example: PI-LED Linear System HD).

Furthermore, stating the melanopic action factor alpha (smel) is mandatory for a reasonable melanopic calculation. All the above-described aspects have to be considered for a reasonable solution. Otherwise it is only a gimmick - just playing around with a small range of CCTs. ■



Peter Haumer is responsible for Product Management at Lumitech Lighting Solution GmbH, Austria. With more than a decade of experience in LED lighting technologies, he specializes in advanced white-light solutions, Human Centric Lighting (HCL), and Lumitech's patented PI-LED technology. He is a frequent speaker and author on spectral light quality, tunable white systems, and next-generation LED lighting technologies.

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¹BLL: BIO-LOGIC LIGHT, PI-LED: Phosphor Innovation LED.



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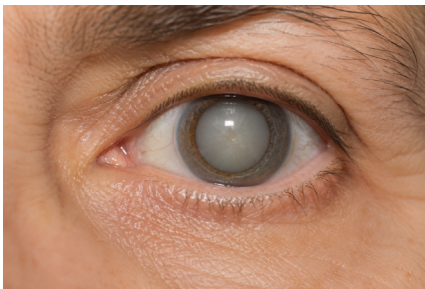


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The Aging Eye and Its Influence on Melanopic Effects

Kevan Shaw, Lighting Consulting and Founder of KSLD

As the owner and operator of a pair of significantly aging eyes I have a considerable interest in how this effects my visual and non visual relationship with light. As a lighting designer who has been active for 50 years, I have had the idea that yellowing of the lens degrades visual performance significantly heavily promoted. Also, the idea that simply increasing illumination levels is a panacea that universally improves vision for the aged eye is the only solution.



A hypermature age-related cortico-nuclear cataract with a brunescent (brown) nucleus. (c) LED professional.

Now I am in my 70s I am happy to assert, from personal experience, that this is not the case. Yes, my vision has deteriorated, however, the problems include lack of focus accommodation (solution: Varifocal eye glasses), increased susceptibility to glare (solution: glare free lighting and reduced illumination levels,) the need for higher contrast in task lighting (solution: good directional lighting sometimes!) reduced visual acuity at low scotopic lighting levels (solution: phone torch!)

As I am keenly interested in non-visual effects of light, I am very interested in the potential effects of yellowing lenses on circadian entrainment and melatonin production. Accordingly, I have taken a look at a lot of academic papers in this field. Many papers have assumed there is a direct correlation between the reduced transmission in the action spectrum frequency for the iPRGC and the corresponding effects on melatonin suppression. Typically, these papers largely combine others' work on these two separate areas and mash the results together. This results in restating the argument for more light and it being adopted in recommendations for provision of melanopically effective light including in DIN/TS 67600.

When people started to look at the situation experimentally things became rather more interesting. Many of these researchers started out to prove the theory that there was a direct correlation but came up with rather different outcomes.

One thing to consider when reviewing research in this field is that, typically, experimental methods rely on measuring melatonin in blood plasma, saliva or urine, at night typically after measuring the control melatonin level before any interventions. This has become the standard way of determining the impact of iPRGC influence. It must be noted that this can only be an indicator of effectiveness of any particular experimental intervention. If we are really interested in the effectiveness of any non-visual lighting effects it is absolutely necessary to conduct follow up studies. These are needed to see what, if any, im-

pact the particular intervention had on long term sleep patterns, daytime alertness, feelings of wellbeing and by implication the actual circadian effects. Such studies are not lab-based experiments but are well in the territory of social psychology to gather subjective experiences for the participants.

Some papers in the area of the aging eye stand out for their results and conclusions:

Two papers by Raymond Najjar separated by 9 years (2014 and 2023) have identified a nonlinear correlation between lens transmission and melatonin suppression. The second endeavors to understand why. Najjar discovered that the peak spectral response moves from 483 nm to 500 nm. The conclusion being that the S-Cone and M-Cone receptors are contributing to the melatonin suppression in older individuals. It is expected that visual receptors in the eye would influence iPRGC responses, after all, the visual receptors are connected to retinal ganglion cells that transmit information to the visual cortex, the Intrinsically Photosensitive Retinal Ganglion cells are noted for connecting information to the Suprachiasmatic Nucleus but will also have connections to visual receptors. The relationships are not fully understood yet particularly in the human eye.

An interesting study by Tomo Nishi in 2020 looks at the effects of cataract surgery where the lens is replaced by a clear or slightly yellow acrylic replacement. In this case the yellowing and reduction in transmission of the normal aging lens is removed with the cataracted lens. This study was carried out over 169 subjects, although this was still considered a small group. The conclusion to this study was that post operatively, after 3 months, an increase in measured melatonin in blood over the preoperative condition was observed in all patients but no difference was shown between those implanted with yellow lenses and those with clear lenses. My consideration is that the improvement in melatonin levels can possibly be ascribed to the removal of the cataract caused changes in the eye rather than removal of the yellow aged lenses. There

is also a confounding factor in that the 3-month time lapse in measurements also crossed distinct seasonal boundaries with consequent changes in natural light exposure that could be, in part, responsible for increased melatonin production.

A paper by Marina Giminez from 2016 looks at this same issue with a much smaller cohort. This concludes that there was no significantly measurable permanent change in melatonin production after cataract surgery. Any short-term change disappears after 12 months post operation. This team also experimented with orange contact lenses in a group of young people simulating the aging of the lens. After 2 weeks there was an increased melatonin measurement ascribed to increased sensitivity due to adaptation to the lenses but no observable change to sleep or melatonin rhythms between the experimental conditions.



Posterior chamber intraocular lens (IOL), 18.5 D, overall length 13 mm, optic diameter 6.0 mm. Photograph: Frank C. Müller, Baden-Baden. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license. [https://commons.wikimedia.org/wiki/File:Hinterkammerlinse_01_\(fcm\).jpg](https://commons.wikimedia.org/wiki/File:Hinterkammerlinse_01_(fcm).jpg)

It is notable that other studies on cataract removal patients have reported immediate, post-operative increases in measured melatonin in blood or urine samples, however these have lacked any longer term follow up studies. Of course this does reinforce the rather simplistic expectation that yellowing of the lens will reduce the response of the iPRGC as expected by the researchers.

Anecdotally, people who undergo cataract surgery report brighter and clearer vision and some color disturbance immediately after the surgery however this experience doesn't persist and 'normal' vision returns after a couple of weeks. Clearly the visual cortex is accommodating the changed information from the eye returning to its learned model of the visual environment. It would seem that the non-visual effects are equally being adapted to a normal expectation in the Suprachiasmatic Nucleus.

Where do we go from here? Well, I think the idea that you automatically provide higher levels of illumination for older people is highly flawed. Certainly for non-visual effects there is no properly researched answer to what provision you should make for the older eye and given the susceptibility to discomfort glare, designing integrative lighting for older people needs very careful handling. There is no doubt that lighting to improve circadian entrainment is very beneficial for older people who generally tend to have poorer sleep patterns. Also care homes and sheltered accommodation are prime projects to consider lighting for non-visual effects as the people living there will be spending more of their time indoors and in an environment where timing of lighting and exposure limits can be more effectively controlled.

Generally, we also need to look at the research methods for non-visual lighting. As mentioned, looking for changes in melatonin levels in blood, urine, or saliva are only indicating limited information that can be overly extrapolated. This inevitably relates to sleep onset or sleep phases when our real interest is in the circadian effects during the working and leisure hours of the day. So far we have not determined specific biochemical indicators for all phases of the circadian rhythm and are reliant on subject reported effects on mood and sleep. We can measure activity and some aspects of performance such as task speed or accuracy. We really do need to undertake more research in the field, in real, live projects to refine our knowledge and inform our design process to develop optimized lighting for health, wellbeing and the visual environment.

Currently the best knowledge we have is in the Manchester group paper of 2022. These recommendations are being adopted in a number of lighting standards including WELL ISO/CIE 8995-1:2005 Lighting of Workplaces, DIN/TS 67600 Complementary Criteria with Regard to Non-Visual Effects of Light and IES RP-46, Supporting the Physiological and Behavioral Effects of Lighting in Interior Daytime Environments. At least if we all follow these recommendations we have a common basis for any anecdotal or subjective research in the future and can be assured we are providing some benefit and not likely to be causing any harm. ■



Kevan Shaw was born and raised in Edinburgh, Scotland. He graduated from Loughborough University of Technology with a B.Sc. in Economic and Technological History and Social Psychology in 1975. He began his career as a lighting designer for rock bands including Jethro Tull, Ultravox, XTC, and Steve Hackett.

In 1989, Kevan returned to Edinburgh to establish Kevan Shaw Lighting Design, specializing in architectural and exhibition lighting. Over the next 35 years, the practice completed more than 800 projects under his leadership before his retirement in 2024. As part of a planned succession, the firm was acquired by EFLA Engineering in 2018 and continues to deliver innovative, high-quality lighting design.

Kevan has long been committed to advancing the lighting design profession and remains at the forefront of developments in the field. A recognized industry thought leader, he continues to support the profession through the International Association of Lighting Designers (IALD), where he serves as an elected director and Chair of the European Regulatory Affairs Committee.

In 2018, Kevan was inducted into the IALD College of Fellows in recognition of his contributions to the art and science of lighting design and his dedicated service to the association. He was named Lighting Designer of the Year at the 2013 LUX Awards and received the inaugural Lifetime Achievement Award at the 2018 LIT Lighting Design Awards.

Today, Kevan continues to provide specialist consulting services to EFLA | Kevan Shaw Lighting Design while enjoying more time to pursue his lifelong passion for steam engines and new adventures.

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Beyond Tunable White: Spectral Control for Circadian Lighting in Healthcare

Xavier Denis, Head of Technical Support and Technical Marketing at Nichia Europe

For readers working with Human Centric Lighting (HCL), the broad principles will be familiar. Light exposure impacts more than visual performance. Healthcare is an application where its timing, intensity and spectrum deserve particular attention. Yet many HCL systems still rely mainly on scheduled transitions between cool and warm white light. That may imitate the appearance of daylight changing, but correlated color temperature (CCT) alone does not define the melanopic stimulus reaching the eye.

The distinction is key in hospitals and residential care where patients and residents spend long periods indoors with limited access to daylight. Sometimes, their daily light exposure is determined almost entirely by electric lighting. Spectral power distribution (SPD), intensity, timing and duration are therefore integral to lighting design, not optional refinements. Staff lighting must also support accurate visual work during examinations and treatment, including in the evening, without disturbing patients.



Xavier Denis, Head of Technical Support and Technical Marketing at Nichia Europe.

Moving Beyond CCT

Two sources with the same CCT can have significantly different spectral power distributions and, at the same photopic illuminance, they can produce different melanopic outputs.

Conventional tunable-white systems typically mix warm-white and cool-white LEDs. Adjusting the balance changes the CCT and usually changes melanopic output too, but the two variables remain closely linked. A system can move smoothly from 2700 K to 6500 K while offering limited control around the peak of the melanopic action spectrum.

Anyone who has specified tunable white will also know that an impressive CCT range on a datasheet says little about the light that ultimately reaches the eye. Distribution, output, surfaces, control settings and occupant position all alter the result.

Responses mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs) are influenced by the complete spectrum at the eye, not the nominal CCT of the source. Melanopsin has an intrinsic peak sensitivity close to 480 nm. Once pre-receptor filtering by the human eye is considered, the melanopic action spectrum defined by the International Commission on Illumination (CIE) peaks at approximately 490 nm.

Morning and daytime lighting should generally provide a higher melanopic stimulus which should decrease toward evening and remain low overnight. This requires control over the quantity and spectral composition of the light. CCT remains relevant to appearance and acceptance but should not be a substitute for melanopic equivalent daylight illuminance (EDI) or a spectral assessment.

Separating the LED Channels

Some HCL systems combine melanopic-enhanced and conventional white LEDs. Both channels, however, emit across broad and overlapping parts of the visible spectrum. Increasing one channel changes melanopic output, photopic output and visual appearance at the same time.

Greater spectral separation between the channels can extend the available control range, allowing higher melanopic output during the day and substantially lower output during the evening without depending entirely on a shift in CCT.

Dynasolis™ from Nichia adopts this approach in a unique way by combining an Azure channel, designed to provide greater output around 480 nm, with a warm-white channel containing much less relative energy in the same region. Mixing the channels allows CCT and melanopic content to be adjusted across a wider range than is normally possible by combining warm-white and cool-white LEDs.

Neither channel is spectrally isolated, nor does it need to be. What matters is the difference between their spectral distributions and the greater control that difference provides at system level.

Why the Cyan Region Matters

Phosphor-converted white LEDs generally use a blue pump near 450 nm to 455 nm, where InGaN emitters can provide high wall-plug efficiency. It is a proven architecture for white light, but its peak output does not align with the peak of the CIE melanopic action spectrum.

Shifting more photometric output towards the 480 nm to 490 nm range can increase melanopic effectiveness. A practical way to achieve it is by using a phosphor-converted cyan or Azure channel, which retains good luminous efficacy and allows the source to be mixed with warm white light.

As shown in **Figure 1**, the Azure LED provides enhanced output in the cyan region, where melanopic sensitivity is highest.

Matching the forward voltage and package height of the two LED types simplifies driver design, board layout and optical integration. Comparable source geometry also supports more uniform mixing through the secondary optic and reduces the risk of visible color separation across the beam.

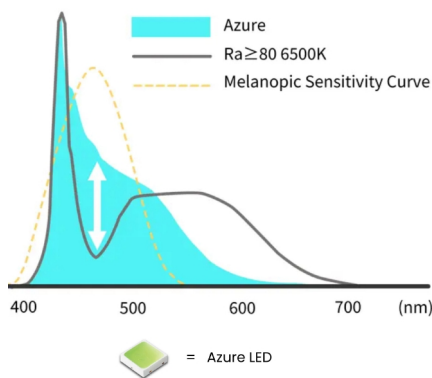


Figure 1: Spectral comparison of an Azure LED and a conventional 6500 K white LED against the melanopic sensitivity curve.

Application in Hospitals

Hospital lighting must reconcile the needs of patients who may receive little natural daylight with those of staff requiring sufficient light for observation, examination, treatment and safe movement at any hour.

Figure 2 illustrates potential applications of the Dynasolis™ LED channels in patient rooms and other hospital environments.

For patients, electric lighting can strengthen the distinction between day and night. During the day, broad-area illumination should deliver light vertically at the eye rather than concentrating only on the horizontal working plane.

This is easily missed. A bed surface, table or floor may satisfy its illuminance target while comparatively little light reaches the patient's cornea. A daytime HCL scene should therefore be assessed at the expected eye position, including when the patient is reclining.

The CIE's 2024 position statement [1] cites a daytime recommendation of at least 250 lx melanopic EDI at the eye for healthy day-active adults. It recommends no more than 10 lx during the three hours before bedtime and no more than 1 lx during sleep.

These figures are not universal prescriptions. The daytime recommendation is based principally on research involving healthy adults. Age, ocular health, medication, clinical condition and previous light exposure can all affect the response. Hospital protocols, safety and individual patient needs must still take precedence.

At night, circadian considerations must be reconciled with observation and treatment. Intensive care, recovery spaces and general patient rooms require different scenes and control strategies.

Examination scenes may require high illuminance, good color rendering and close glare control. Lower-output scenes can support routine observation or circulation without exposing patients to short-wavelength-rich light throughout the night.

The credible objective is not to claim that lighting accelerates treatment. It is to support visual care, reinforce day-night contrast and avoid exposure likely to disrupt sleep or circadian timing.

Application in Retirement and Care Homes

The age-related changes affecting vision are well understood within the lighting industry. Reduced retinal illuminance, lower contrast sensitivity and slower adaptation mean that older residents may require substantially more task light than younger occupants, particularly for reading, crafts and personal care.

The appropriate level still depends on the task, eyesight, surface reflectance, contrast and glare. Simply adding more lumens can produce a brighter but less comfortable environment.

Care settings must also account for residents living with dementia. Strong shadows, reflections, abrupt contrasts and certain floor patterns may be misinterpreted as obstacles or changes in level. Good vertical illumination can support better facial recognition, communication and orientation.

During the morning and throughout the day, higher melanopic exposure at the eye

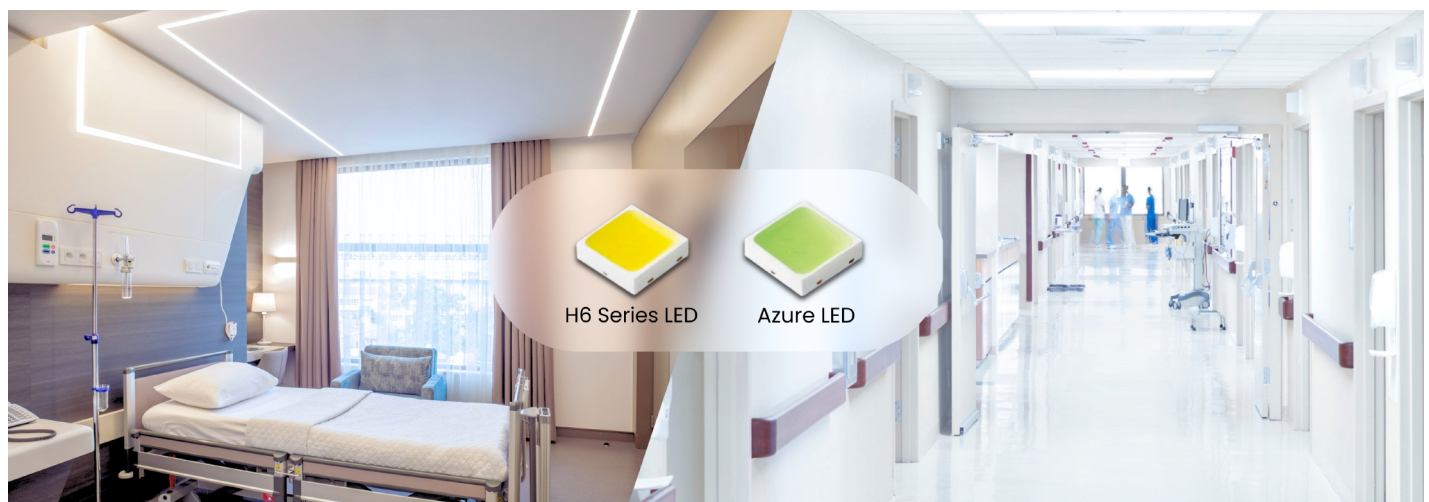


Figure 2: Illustrative hospital applications for Dynasolis™, combining Azure and warm-white LED channels to support adaptable lighting throughout the day and night.

can reinforce the daytime signal. In the evening, both illuminance and melanopic content should fall progressively. A warmer appearance may help to communicate that transition, but CCT does not tell the full technical story. The SPD and resulting melanopic EDI remain more useful.

Figure 3 illustrates a possible daily lighting sequence, moving from energizing light during active hours towards warmer, more relaxing light in the evening.

At night, lighting should be limited to what is necessary for orientation, observation and care. Distribution can be as influential as spectrum. Low-level light directed towards the floor may support movement

while reducing exposure at the eye, if glare, adaptation and fall risks have been properly considered.

Some studies in care settings [2] have reported improvements in daytime activity and sleep following scheduled light exposure, although the results vary by population, dose and research method. However, a larger 2026 study [3] found no significant improvement in actigraphic sleep or rest-activity after three months of biodynamic lighting. Any claims of specific medical benefit should therefore be treated with caution.

From LED Spectrum to Delivered Exposure

Dynasolis supplies the spectral components required to create a wider range of melanopic output than conventional tunable-white systems. As shown in **Figure 4**, this is achieved by combining an Azure LED with enhanced cyan-region output and an H6 Series warm-white LED with low melanopic content. The LED component itself, however, does not determine the effect on the occupant. That result depends on the complete luminaire, its optical distribution, output, position and control schedule. Surface reflectance, daylight contribution, room geometry and the occupant's orientation also influence the result.

Healthcare HCL should therefore be designed and commissioned using measurements at representative eye positions, rather than relying only on luminaire output, horizontal illuminance or a scheduled CCT value. Melanopic EDI must sit alongside visual requirements, glare, color quality and energy use.

Spectral tuning offers more than a broader change in color appearance. Its value is the ability to manage melanopic content more deliberately while preserving the visual and practical performance required from a healthcare lighting installation. ■

For more information on Dynasolis from Nichia, visit: https://led-ld.nichia.co.jp/en/product/lighting_dynasolis.html

Contact NEG_Mktg@nichia.com

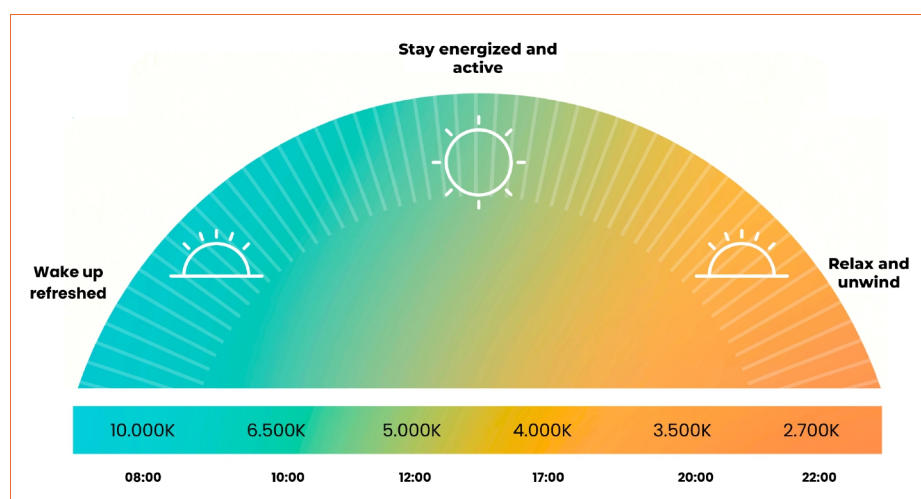


Figure 3: Example of a daily lighting sequence using Dynasolis™, transitioning from energizing, high-CCT light during the day to warmer, more relaxing light in the evening.

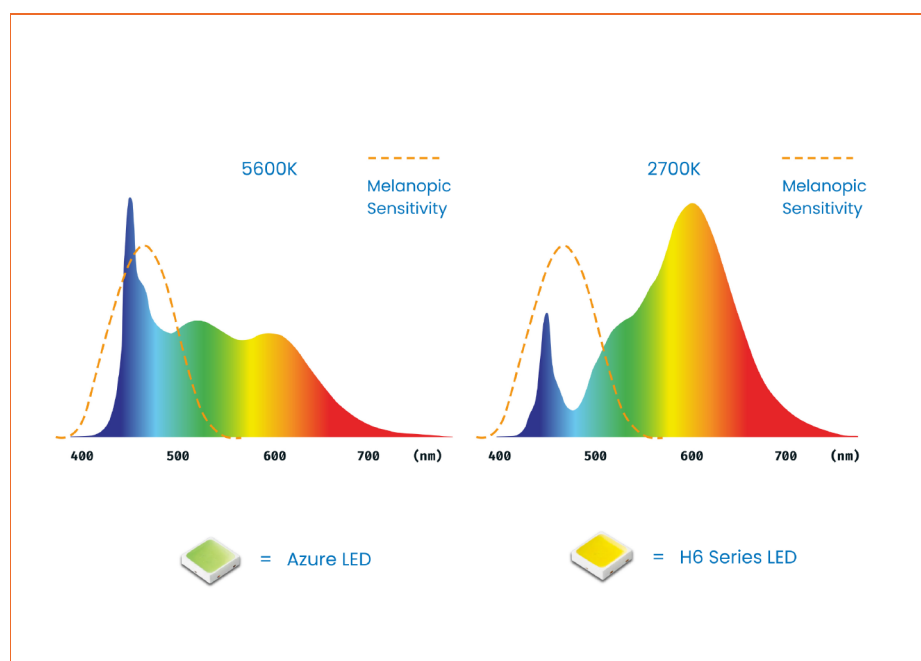


Figure 4: Dynasolis™ spectral distributions: an Azure LED with enhanced cyan-region output and an H6 Series warm-white LED with low melanopic content.

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Human Centric Lighting braucht fundiertes Wissen – die LiTG als Plattform für Lichtkompetenz.

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im Bereich der über das Auge vermittelten,
nicht-visuellen Wirkungen von Licht



51

LiTG-Fachgebiet
Melanopische Lichtwirkungen

ÜBER DIE NICHT-VISUELLE WIRKUNG DES LICHTS AUF DEN MENSCHEN



32

HCL – Licht für den Menschen. Wissen, das wirkt.

Human Centric Lighting unterstützt unseren biologischen Rhythmus, fördert Wohlbefinden, Leistungsfähigkeit und Gesundheit. Die beiden Fachgebiete des LiTG-Fachgebiets „Melanopische Lichtwirkungen“ bieten fundiertes Wissen und praxisnahe Leitfäden für Planung, Bewertung und Umsetzung moderner Lichtlösungen.



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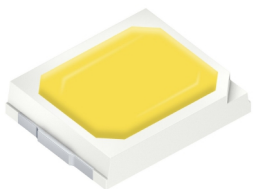
Adaptive Lighting — How Scalable LED Platforms Power the Next Generation of Smart Indoor Lighting

Florian Lex, Head of Applications Engineering Industry & Professional EMEA at ams OSRAM

As building digitalization accelerates, the requirements for professional indoor lighting are fundamentally changing. Lighting systems are evolving from standalone light sources into connected subsystems within smart building infrastructures that integrate sensing, communication, and control. To achieve this, Adaptive Lighting combines high-performance LED technology with intelligent control, providing the foundation for energy-efficient, flexible, and future-ready lighting solutions.

At the same time, requirements for the LED components deployed are increasing. In addition to high luminous efficacy and light quality, precise dimming, color consistency, long-term reliability, as well as integration with digital control and building automation systems are gaining in importance. Scalable LED platforms are therefore emerging as a key technological enabler of adaptive lighting systems.

This article examines how Adaptive Lighting is becoming the next stage in the evolution of modern indoor lighting, the requirements it places on LED technologies, and why scalable LED platforms — as illustrated by the OSCONIQ™ product family from ams OSRAM — provide an essential foundation for the next generation of intelligent lighting systems.



OSCONIQ™ E 2835 Cyan Enhanced.

Professional indoor lighting is currently undergoing a profound technological transformation. In recent years, LED technology has primarily delivered gains in energy efficiency and service life. Today, the focus is shifting toward digitalization, smart buildings, and sustainable operating concepts.

Sensors continuously collect data on occupancy, available daylight, and space utilization, while modern communication interfaces enable data exchange with other building automation systems. The resulting lighting solutions can adjust their operating parameters in real time as conditions change, optimizing both energy use and occupant comfort.

With Adaptive Lighting, indoor lighting is evolving from a static installation into a dynamic system that integrates LED technology, sensing, and intelligent control in one unified solution.

Adaptive Lighting as a System Concept

Adaptive Lighting refers to lighting systems that automatically adjust lighting parameters—such as luminous flux, color temperature, or illuminance—in response to changing environmental conditions. The aim is to optimize occupant comfort, energy efficiency, and building operations while establishing lighting as an integral part of smart buildings.

From Human Centric Lighting to Adaptive Lighting

Human Centric Lighting (HCL) has played a defining role in the development of modern indoor lighting. Whereas earlier lighting concepts focused primarily on illuminance

and energy efficiency, HCL placed greater emphasis on people and their visual needs.

However, the digitalization of modern buildings has expanded these requirements. Flexible workplace models, changing space occupancy, and increasingly stringent sustainability requirements call for systems that continuously adapt their operating parameters to actual environmental conditions.

Adaptive Lighting builds on this user-centered HCL approach and extends it into a broader system perspective. In addition to occupant needs, the control strategy now incorporates sensor data, energy efficiency, building operations, and digital control architectures. Sensors capture information such as available daylight, occupancy, and space utilization and make it available to an intelligent control system. Based on these inputs, the system automatically adjusts illuminance—and, in tunable white systems, color temperature—to suit the way the space is being used.

Lighting is also becoming an integral part of smart buildings. Standardized communication protocols such as DALI-2 and DALI+ allow lighting to be integrated into building automation systems and networked with other building services.

Requirements for Modern LED Technologies

Adaptive lighting systems place demanding requirements on the underlying LED technology. Alongside excellent light quality, energy efficiency remains a central design parameter. However, adaptive systems realize their full energy-saving potential only when intelligent control is paired with highly efficient LED components. Functions such

as daylight harvesting and occupancy-based lighting control can deliver sustained reductions in energy use without compromising light quality or occupant comfort.

As tunable white and multi-channel systems become more widespread, the reproducibility of lighting characteristics is also becoming increasingly important. LEDs must reliably maintain luminous flux, chromaticity, and color rendering even through frequent dimming cycles, changing temperatures, and varying operating conditions.

At the same time, demand is growing for scalable LED platforms that combine various power classes, color temperatures, and color-rendering options on a common technological basis. This approach reduces development and qualification effort while allowing different luminaire families to be implemented on a consistent platform.

A Scalable LED Platform for Adaptive Lighting: The OSCONIQ™ Example

The demands placed on today's adaptive lighting systems extend well beyond high luminous efficacy. What is needed are LED platforms that combine light quality, precise controllability, long-term reliability, and system flexibility on a common technological basis.

The OSCONIQ™ product family from ams OSRAM is one prime example. Developed specifically for professional indoor lighting, it offers multiple power classes, color temperatures, and color-rendering options within a common platform architecture. This enables a wide range of luminaire concepts to be implemented on the same technological basis. For luminaire manufacturers, the result is greater design flexibility, reduced development effort, and a consistent system architecture across product families.

A key feature of the platform is the high reproducibility of its lighting characteristics. Precise chromaticity consistency supports a uniform appearance even in large-scale lighting installations, while stable performance across the full operating range enables the reliable implementation of dynamic lighting scenarios.

The platform's high energy efficiency also supports energy-optimized lighting concepts. Combined with sensing, intelligent control, and building automation, functions such as daylight harvesting and occupancy-based lighting control can realize their full potential, reducing both energy consumption and operating costs. At the



Applications with the OSCONIQ™ product family from ams OSRAM.

same time, the platform can be reliably integrated into digital control and building automation systems, supporting the development of intelligent, connected building infrastructures.

Application Example: Adaptive Lighting in a Modern Office Building

A modern office building with digitally connected lighting illustrates how these requirements can be implemented in practice. The luminaires are linked through sensors and a central building automation system. Occupancy sensors detect the use of individual work areas, while daylight sensors continuously measure the natural light available. Based on this information, the system automatically adjusts illuminance to actual demand. In areas equipped with tunable white lighting, color temperature is also controlled according to the time of day and how the space is being used.

In the morning, the system provides higher illuminance levels and cooler color temperatures to support alertness and activity. As more daylight becomes available, the lighting control system automatically reduces the contribution of electric lighting, helping to lower energy consumption. Throughout the day, illuminance and color temperature are continuously adapted to current use. Unoccupied work areas are automatically dimmed or switched off, while heavily used zones continue to receive the light they require.

Reliable operation depends on LED components that maintain stable lighting characteristics over time, even with frequent switching and dimming. High chromaticity consistency, consistent light quality, and long-term reliability are essential for uniform lighting conditions and low-maintenance operation.

Conclusion

The evolution from Human Centric Lighting toward Adaptive Lighting reflects the transformation of modern indoor lighting: Light is increasingly becoming an intelligent element of digitally connected buildings. Sensing, communication, and automation enable lighting systems to adapt flexibly to changing patterns of use and environmental conditions.

This shift is driving higher expectations of LED technology. In addition to high light quality and energy efficiency, key requirements include reproducible lighting characteristics, precise controllability, long-term reliability, and integration with digital control and building automation systems.

Scalable LED platforms provide the technological foundation for meeting these requirements. The OSCONIQ™ product family demonstrates how various power classes, color temperatures, and color-rendering options can be implemented within a common platform architecture. This enables luminaire manufacturers to develop efficient, future-ready lighting solutions that can be flexibly adapted to different applications.

As building digitalization advances, Adaptive Lighting will become a core component of intelligent indoor lighting, helping to improve energy efficiency, occupant comfort, and system flexibility in equal measure. ■

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Human Centric Lighting: More Than Just Good Vision

Birthe Bittner, Head of Application Management, Zumtobel Lighting

Lighting that is tailored to human needs can promote well-being, improve productivity in everyday working life and speed up recovery processes. Investments in Human Centric Lighting therefore often pay for themselves many times over.

The requirements for modern building lighting are changing. Workplaces are becoming more flexible, educational institutions more diverse, healthcare facilities are grappling with staff shortages, and industrial production sites must balance efficiency with staff well-being. Against this backdrop, Human Centric Lighting (HCL) is becoming increasingly important.



Birthe Bittner is Head of Application Management at Zumtobel Lighting, where she leads the development of application-focused lighting concepts for industrial and professional building environments. She joined Zumtobel in 2007 as a Lighting Application Expert and has played a key role in advancing innovative lighting solutions that combine energy efficiency, sustainability, and user-centric design. Birthe holds a degree in Media Technology from the Technical University of Ilmenau and is a frequent speaker on topics including industrial lighting, Human Centric Lighting, and direct current (DC) lighting for sustainable buildings.

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Light is far more than meeting regulatory lighting requirements as it also influences wellbeing, performance, orientation and health. In doing so, light fulfills two fundamental functions: on the one hand, it creates safe and comfortable spaces; on the other, it has a biological and emotional effect on people by significantly influencing the sleep-wake cycle (circadian rhythm), hormone release, concentration, mood and general well-being.

Human Centric Lighting (HCL) addresses both of these levels. The aim is to replicate natural lighting conditions with artificial light while taking into account the specific requirements of a certain space. At the heart of HCL, therefore, lies a holistic lighting concept that brings together architecture, technology and people. Factors such as light color, illuminance, dynamics, glare control and individual controllability play a decisive role in this.

Lighting Concepts for a Life in Harmony with Nature

Scientific findings from lighting research, medicine, ergonomics and architecture are incorporated into the development of new HCL solutions. In addition, there is a focus on energy efficiency, sustainability and digital connectivity. Modern lighting systems therefore combine high-quality LED technology with intelligent sensors and lighting management systems. This results in dynamic lighting scenarios that automatically adapt to daylight, the time of day, room usage or individual needs. Unlike static lighting, these flexible lighting concepts support people throughout their daily routine – from concentrated work and creative phases right through to relaxation.

Smart Solutions for a Range of Requirements

Human Centric Lighting is always application specific. That is why Zumtobel develops solutions for a wide variety of building types and usage scenarios. These include, among others:

- Dynamic Tunable White systems with variable color temperature to replicate the natural progression of daylight
- A light spectrum similar to daylight – the Zumtobel Spectrum
- Daylight-dependent lighting control and presence-based controls
- Individual adjustment of the light color and intensity of workplace lighting
- Intelligent lighting management systems for networked buildings, for integration into smart buildings and for digital building management systems

Adaptive Lighting Solutions for Inclusive Spaces

When developing appropriate usage scenarios, it is important to bear in mind that people differ in terms of age, biological conditions, working styles and health needs. This diversity places particular demands on lighting, as not everyone perceives light in the same way. Older people often require higher illuminance levels. People with visual impairments benefit from particularly uniform, glare-free lighting. Some people may be sensitive to flicker or high contrasts. Flexible working models also often mean that different activities take place in the same rooms. HCL takes these individual needs into account – with adaptive lighting solutions that can be tailored to both groups and individual users. This way it is possible to create inclusive spaces in which as many people as possible feel comfortable and can carry out their tasks to the best of their ability.

Office Buildings – Combining Productivity and Well-being

Human Centric Lighting can also support various work processes in office environments. Cooler, energizing light can promote concentration during demanding tasks. Warmer lighting moods create a pleasant atmosphere for meetings or informal communication. Dynamic lighting sequences are modeled on natural daylight and support the body's circadian rhythm.

For businesses, lighting thus becomes a key component of modern workplace concepts and an employee-focused corporate culture.

Schools and Educational Institutions – Effective Learning at any Time of Day

Learning is a highly complex process. Attention, motivation and concentration fluctuate considerably throughout the day. Human Centric Lighting therefore offers schools and educational institutions the opportunity to provide targeted support for different teaching situations.

Stimulating lighting atmospheres encourage focused work, while calmer light colors are used, for example, during group work, presentations or creative sessions. At the same time, teachers also benefit from a pleasant working environment and uniform lighting throughout the classroom.

Human Centric Lighting even plays a key role in inclusive education. This is because flexible lighting concepts allow better provision for different learning requirements, individual needs and neurodiverse pupils. To this end, Zumtobel develops lighting solutions that combine both educational requirements and high energy efficiency.

Hospitals and Care Homes – Greater Well-being, Faster Recovery

However, few sectors stand to benefit as much from Human Centric Lighting as the healthcare sector. This is because patients often spend many hours, days or even weeks without sufficient exposure to natural daylight. This can disrupt their sleep-wake cycle and significantly delay their recovery. Dynamic lighting simulates a natural daily rhythm and creates pleasant lighting atmospheres throughout the day. At the same time, care workers and medical staff benefit from high-quality lighting that facilitates both precise work and ergonomic working conditions.

Light also plays a central role in care homes. Older people, in particular, are sensitive to changes in their circadian rhythm. This can lead to general restlessness, sleep disturbances and night-time activity. Human Centric Lighting supports both the well-being of residents and the working conditions of staff – which helps to counteract the shortage of skilled workers.



Lighting that is tailored to human needs can promote well-being, improve productivity in everyday working life and speed up recovery processes.

Industry – Light as a Factor in Productivity

Human Centric Lighting is also becoming increasingly relevant in industrial settings. This is because manual production processes often place high demands on concentration, precision and safety. Employees who work shifts, in particular, spend a large part of their working hours in artificially lit halls. This can easily throw the so-called 'internal clock' out of sync. Intelligent lighting systems featuring HCL therefore not only provide optimal illumination for workstations, reduce glare and improve visual perception, but also help to support employees' biological rhythms through dynamic lighting sequences. This is particularly beneficial for staff on early, late and night shifts. Human Centric Lighting thus combines three key objectives in the industrial sector: safety, efficiency and employee wellbeing.

Sustainability and Digitalization

Moreover, LED technology, intelligent control systems, daylight integration and demand-based regulation result in high-quality lighting solutions with a long service life, low maintenance requirements and low energy consumption. Human Centric Lighting is therefore a key component of sustainable buildings, supporting ESG targets as well as certifications such as DGNB, LEED and BREEAM. Through integration into digital building management systems, lighting also becomes part of smart buildings, in which lighting, sensor technology and building services communicate with one another.

Consistently Geared Toward the Building's Use

Finally, Human Centric Lighting represents a fundamental shift in perspective: away from a purely technical view of lighting, toward people-centered lighting design. Zumtobel consistently pursues this approach. Scientifically sound lighting solutions, intelligent control systems and high-quality light create spaces that promote health, well-being and productivity in equal measure. Whether in offices, schools, hospitals, care homes or industrial settings – every usage scenario presents its own requirements, which can be met through flexible and bespoke lighting concepts.

Light thus becomes a strategic component of modern architecture. It not only provides visibility but also supports people in their everyday lives, promotes inclusion and diversity, while at the same time making an important contribution to sustainability and energy efficiency. Human Centric Lighting is therefore far more than just a lighting trend – it is a forward-looking approach to buildings that are consistently tailored to the needs of their users. ■



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Human Centric Lighting – Light That Puts People at the Center

TRILUX

Electric lighting has made human work independent of the sun's course and the natural rhythm of day and night. But light does more than provide the illuminance required for vision – it also has emotional and non-visual effects. Human Centric Lighting (HCL) concepts incorporate the growing body of knowledge on the non-visual aspects of light into the design of integrated, smart lighting solutions. The goal: a holistically planned lighting scheme that supports human health, well-being, and performance.

The Non-visual Effects of Light

Human development is closely linked to natural daylight, which plays a key role in synchronizing the sleep–wake cycle and other circadian processes. But how exactly does daylight affect people? The non-visual effects of light are primarily mediated by a specialized light-sensing system in the retina. In addition to rods and cones, the retina contains intrinsically photosensitive retinal ganglion cells (ipRGCs), which are particularly sensitive to blue–cyan light around 480 nanometers. Signals from these cells reach, among other areas, the suprachiasmatic nucleus (SCN) – a region in the brain regarded as the body's master clock. In this way, light influences various physiological processes, including the sleep–wake cycle and melatonin and cortisol rhythms.

During daytime, bright light with a strong melanopic effect can promote alertness and attention and help stabilize the circadian rhythm. This activating effect is not primarily due to melatonin suppression, since daytime melatonin levels are low. In the evening and at night, however, light with high melanopic effectiveness can inhibit the natural rise in melatonin secretion. Light with lower melanopic effectiveness generally interferes less with this increase. Appropriately designed lighting can better support adaptation to biological night and readiness for sleep. Critical factors include not only color and spectral composition, but also intensity, duration of exposure, and time of day.

Human Centric Lighting concepts take these relationships into account to holistically align the visual and non-visual aspects of lighting with human needs.

Normative and Design Foundations

Despite growing scientific evidence, Human Centric Lighting is not yet mandated in Europe as a stand-alone lighting concept. In recent years, however, important recommendations and planning foundations have emerged that, alongside visual requirements, increasingly address circadian and, to some extent, emotional effects of light.

A key starting point is the 2016 position paper issued by the German Electrical and Electronic Manufacturers' Association (ZVEI). It describes HCL as a lighting concept that incorporates not only visual requirements but also the emotional and biological effects of light. The aim is to support people's natural circadian rhythm and, under appropriate conditions, promote well-being, alertness, concentration, and performance.

ZVEI recommends making the most of available daylight and adapting electric lighting over the course of the day to match the current visual and biological requirements. This can involve adjusting illuminance, spectral composition, and correlated color temperature. However, the position paper does not stipulate universally binding values for lux levels or color temperatures across all use cases. Instead, design should reflect use, time of day, spatial conditions, and the occupants' needs.

The European standard DIN EN 12464-1 also refers to the non-visual effects of light and notes that they can or should be considered in lighting design. This expands the perspective beyond the narrow fulfilment of visual task requirements. In addition to adequate lighting quality and visual comfort, aspects of spatial perception and the temporal and biological impact of light can be incorporated in planning. The standard does not, however, define comprehen-

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sive, stand-alone HCL requirements nor set generally applicable thresholds or minimum values for circadian-effective lighting.

Complementing this, DIN/TS 67600 outlines scientific foundations and planning relationships for non-visual light effects. Like the ZVEI position paper, it recommends fully leveraging available daylight in design. Electric lighting can supplement daylight when it is insufficient or does not ensure the required lighting quality. DIN/TS 67600 explicitly positions itself as a complement to existing lighting standards. As a technical specification, it provides planning guidance but does not define universally binding HCL thresholds or minimum requirements.

Overall, a clear trend is evident: Europe still largely lacks independent, binding HCL requirements. At the same time, non-visual and emotional aspects of light are gaining importance in recommendations, technical specifications, and professional lighting design. Modern lighting concepts should therefore not only enable good, comfortable vision but also support non-visual and emotional effects through appropriate temporal and spectral light design.

Certifications – HCL Earns Points

Many organizations use building certifications to demonstrate the quality and sustainability of their properties according to recognized and internationally comparable criteria. Certification systems such as the WELL Building Standard, LEED, and BREEAM increasingly evaluate lighting not only for energy efficiency and visual quality but also for health, well-being, and user comfort. The applicable requirements depend on the specific certification, version, and rating system.

Compared with many traditional building certifications, the WELL Building Standard places a particularly strong emphasis on occupant health and well-being. In the Light category, measures aimed at creating a circadian-supportive lighting environment are assessed. Depending on the WELL version and selected criteria, relevant aspects include making optimal use of daylight, providing sufficient melanopic stimulus at workstations, effectively limiting direct and reflected glare, and enabling individual lighting control.

For assessing non-visual light effects, melanopic metrics such as melanopic Equivalent Daylight Illuminance (melanopic EDI) are used, based on evaluation ap-

proaches developed by the International Commission on Illumination (CIE). The objective is to provide a circadian-supportive, alertness-promoting light environment during the day while avoiding unnecessary activation from light in the evening and at night.

BREEAM, too, increasingly takes a holistic view of light quality within Health and Well-being. Depending on version and scheme, aspects such as daylight provision, views to the outside, glare control, and user-centered lighting design may contribute to the assessment. Dynamic HCL systems are not explicitly required; however, when correctly designed, documented, and operated, they can help fulfil individual criteria, for example in visual comfort, controllability, and user comfort.

The US-based LEED certification follows a similar, though not identical, approach. Within Indoor Environmental Quality (EQ), criteria include access to daylight, glare control, interior lighting quality, and individual control options. LEED does not explicitly mandate HCL; however, dynamically controllable lighting systems can help meet several EQ requirements.

In summary, HCL can make a valuable contribution to meeting selected building certification criteria – provided systems are designed to requirements, professionally implemented, and properly documented.

Different Quality Levels in Lighting Design

The basic obligation of lighting design is to create lighting that enables good visual conditions. The primary focus must be on meeting recognized requirements from standards, regulations, and building specifications. A conventionally designed scheme – for example a symmetrical, grid-based arrangement of luminaires with proven light distributions – can deliver standard visual comfort. However, such a purely functional approach overlooks lighting's enormous design potential.

The next quality level integrates factors such as architecture, spatial lighting effects, work situations, and corporate culture. The concept aligns with sightlines and showcases objects and furnishings attractively, for example with zoned, material-appropriate lighting. This elevates spatial quality and enhances the user experience.

A further step is a holistic Human Centric Lighting concept. To optimize conditions for occupants, such lighting design pro-

vides excellent visual conditions and an attractive spatial effect – for example by intelligently combining general and accent lighting – while actively supporting well-being, strengthening the circadian rhythm and, depending on context, enhancing alertness, concentration, or relaxation. Concepts at this level are individualized, delivering solutions beyond the standard.

The Building Blocks of an HCL Lighting System

The building blocks of a holistic scheme are HCL-capable luminaires working in concert with a lighting management system and sensors. As a full-service provider, TRILUX supplies all required components from a single source to ensure simple, reliable implementation. So-called Tunable White luminaires can dynamically vary their color temperature between warm white (2,700 K) and daylight white (6,500 K). Tunable White is available across central TRILUX solutions – from the universal Yonos lighting system and Rail trunking to the E-Line Pro continuous-row system. This enables HCL applications across diverse use cases, including office, industry, and retail.

Luminaires are networked via a lighting management system and combined with the desired sensors. Here, too, TRILUX offers a suitable solution for every project with the LiveLink ecosystem. Networking can be wireless or via DALI; even hybrid networks combining DALI and wireless are possible with the new LiveLink Wireless Controller. Conveniently, core HCL functions such as a circadian control curve are pre-installed in the LiveLink ONE app and can be activated with a few clicks. The control curve dynamically adjusts luminaire color and intensity over a predefined daily profile.

Sensors are another indispensable building block in modern lighting management. They capture parameters such as available daylight and presence. Based on this data, the system intelligently adapts lighting to on-site conditions. This is not only convenient – it also enables significant energy savings by providing light only when and at the intensity actually required. For optimal sensor-based control, central parameters such as mounting height and detection area must be tailored to the project. TRILUX offers the in-house developed InTuSens sensor family with a solution for every application and mounting situation. The sensors are available in five series and can be flexibly configured per project.

Planning Practice: Digital and Concurrent with BIM

Lighting concepts are increasingly designed digitally and collaboratively. The shift to network-based collaboration among all stakeholders on a shared building model highlights the significant differences between digital and traditional lighting design. A key driver is the BIM-based planning method (Building Information Modelling). It enables all parties to carry out individual planning steps early and often concurrently. Trades, disciplines, and stakeholders such as facility management collaborate across the entire operational lifecycle of a building.

A foundation within the BIM method is the EIR (Employer's Information Requirements). These define not only the quality requirements for lighting and lighting management planning (e.g., for HCL), but also the software and IT infrastructure to be used in the project and the required information depth and data formats for digital planning.

This means planners need significantly more data for BIM than for traditional lighting design. A BIM dataset includes not only photometrically relevant information such as luminous intensity, light distribution, and color characteristics; it also contains numerous other planning-relevant data points, for example luminaire geometry and weight as well as sustainability information. The result is a digital luminaire twin that integrates seamlessly into the building's digital twin. To meet quality expectations, TRILUX provides, for example, Revit luminaire planning data and current lighting design formats.

For lighting design, it is also advisable to apply a process guideline such as the Lighting System Design process in accordance with DIN CEN/TS 17165 (**Figure 1**).

Overall, BIM presents an opportunity for lighting design to be integrated much earlier into the building planning process, strengthening the role of high-quality lighting solutions – especially HCL concepts.

Demonstration and Reference Project: Scherler AG, Chur, Switzerland

Scherler AG is one of Switzerland's leading engineering companies for electrical and building services. With the construction of its own office building, Scherler AG implemented a demonstration and reference project for modern building technology. Lighting, automation, communications, and

energy supply were designed as networked systems. The TRILUX luminaires used are not only light sources but part of an intelligent building infrastructure.

A key lighting goal was the implementation of an HCL solution for work areas. In addition to photometric performance, luminaire design, light quality, and harmonious integration into the interior architecture were central.

All luminaires in the building were networked via the LiveLink lighting management system. The HCL control curve, which dynamically adjusts brightness and light color over the course of the day, was customized for the project. The color temperature varies between 3,000 K and 5,000 K, with the highest values around midday to support the circadian rhythm (**Figure 2**).

Innovative Building Technology: The Zehnder Group Center of Climate

Zehnder Group Deutschland GmbH is the German sales company of the Swiss Zehnder Group AG. The company develops and markets solutions for a healthy and energy-efficient indoor climate. Requirements for sustainability and well-being were correspondingly high for the forward-looking new company headquarters in Lahr. The 5,000 m² building houses offices and conference/meeting rooms for employees, a laboratory, and rooms for internal and external training. The holistic concept addresses not only energy efficiency but also creates an attractive overall atmosphere to support users in their tasks.

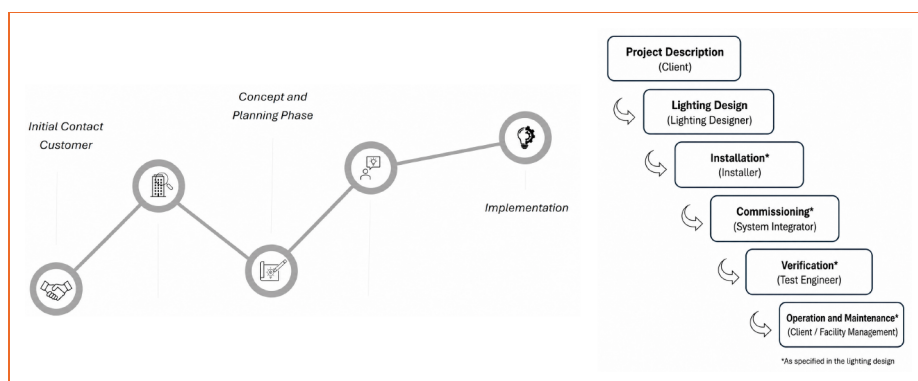


Figure 1: The lighting design process (left). Implementation phases according to DIN CEN/TS 17165 (right).



Figure 2: Scherler AG: The new office building features an HCL solution with TRILUX luminaires and the LiveLink lighting management system.

An innovative building block is the integrated Wellumic lighting solution co-developed by sun-shading specialist WAREMA and TRILUX. Wellumic coordinates lighting and solar shading as an orchestrated system. Rather than blocking daylight, the shading is controlled to admit maximum useful daylight into the space. An algorithm-based control strategy prevents excessive heat gains from direct sunlight in summer and the associated need for energy-intensive cooling. Sensors measure light conditions inside and outside – and automatically optimize the blind position and slat angle of the external venetian blinds and the lighting accordingly.

Workplace lighting is provided by a direct/indirect pendant luminaire with HCL. It contributes only the portion required to achieve the desired overall light level in the room. Users can, of course, override automatic control – for instance to set blinds individually or switch to an activating or relaxing lighting scene (**Figure 3**).

Wellumic Study on HCL and User Acceptance

What illuminance and color temperature are required for non-visual effects – and how can high user acceptance be achieved? WAREMA and TRILUX investigated this in a preparatory Wellumic study. The Fraunhofer Institute for Building Physics (IBP) joined as a cooperation partner and adapted the measurement acquisition and evaluation system in close coordination with WAREMA to the study design. Numerous lighting settings with different color temperatures in direct and indirect components were examined over the course of the day. The study showed that a cool, blue-tinged indirect ceiling illumination combined with warm-white direct task lighting achieved the highest user acceptance and was rated as particularly pleasant and activating. A daylight-white ceiling evokes the blue sky, while the warmer direct light simulates sunlight. Employees felt more active and focused as a result. The overall lighting level was also adjusted dynamically throughout the day, which likewise had a positive effect on well-being and activity levels in the study.

Beyond this, TRILUX participates in numerous research projects aiming to generate new insights into the non-visual effects of light – and translate existing knowledge into market-ready, lighting-technical solutions. Of particular interest are field studies, e.g., in industry or mobility, which also demonstrate positive lighting effects.

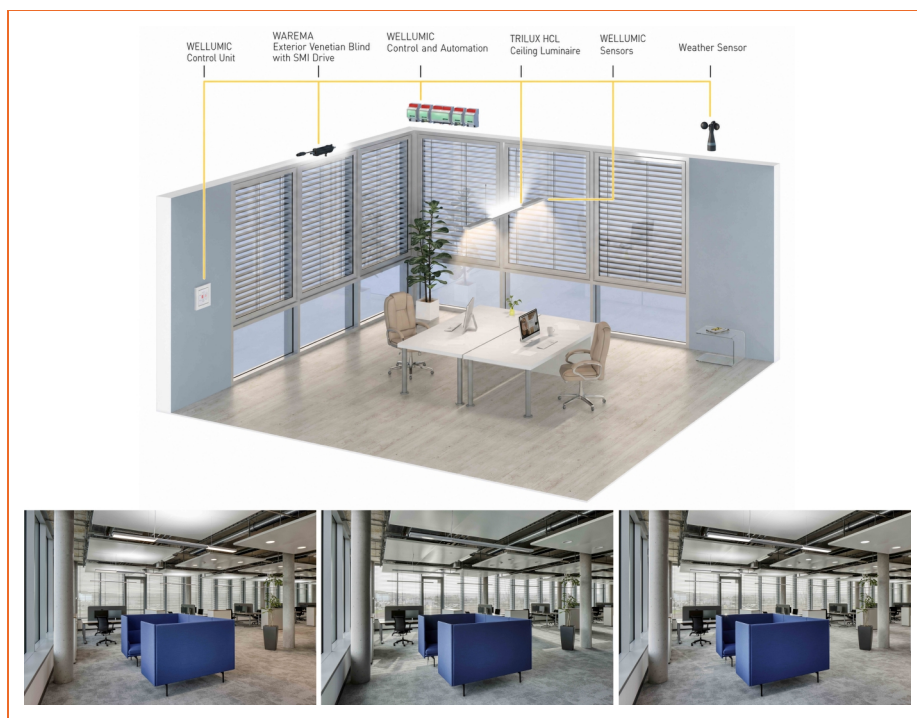


Figure 3: Wellumic system diagram (top). In the morning and evening, the HCL system provides warm-color lighting (bottom, left). In the afternoon, the exterior venetian blinds redirect sufficient daylight into the room while preventing glare (bottom, middle). When weather conditions limit the available daylight, artificial lighting supplements it with a color temperature appropriate for the time of day (bottom, right).

Project Connected Chronolite – Project code: FKZ: 45KI11A011

Electric lighting is ubiquitous – yet its impact on health and well-being is widely underestimated. It is about more than brightness. Light influences our concentration, mood, and sleep. Everyone knows what it feels like to sit in the wrong light: too harsh, too cool, too dark. Especially while travelling, in vehicles, or in waiting areas, the option to adjust lighting individually is often missing. This is where the Chronolite research project came in: the aim was to develop a cross-modal, networked lighting system for the mobility sector that aligns with the human circadian clock. Chronolite set out to prepare an industry standard and digitally connect mobility environments – aircraft, transit areas, cars, and trains – from a lighting perspective. At the center is the Chronolite Data Hub, a secure data platform that uses an AI-based model to integrate scientific evidence, empirical insights, and user feedback to generate suitable lighting scenarios. These scenarios take into account individual factors such as age, gender, chronotype (status of the biological clock), location, and time of day to support user well-being and activity in a targeted way. The system is complemented by the Chronolite app, which captures personal settings, routines, and preferences. Chronolite was conceived

from the outset as an interdisciplinary initiative – with partners from research, industry, design, and practice. Cross-disciplinary collaboration enabled an integrated approach: from chronobiological research and app development through to practical trials in real test environments. As the initiator, Hamburg-based jetlite GmbH led the consortium and coordinated all key work packages. Together with its partners, the consortium developed and tested the system conceptually, technologically, in terms of design and organization. TRILUX was an associated partner responsible for planning and real implementation of networked, dynamic lighting in transfer and lounge areas in the airport context. Throughout the project, TRILUX contributed lighting and controls expertise, making an important contribution to the project's insights and outcomes. Thanks to the consortium's broad expertise, Chronolite holistically addressed the complex requirements for adaptive, personalized lighting in the mobility sector.

Statement from consortium lead Dr Achim Leder: *“From the Chronolite project we gained the crucial insight that truly effective, user-centered lighting must go far beyond static solutions. We have developed an IoT-networked lighting system that dynamically adapts to the lighting needs of people on the move – along their entire travel chain. The positive results for users*

are immense: Chronolite enables personalized light experiences that respond in real time to the time of day, location, and individual user needs. Imagine: through the Chronolite app, users are directly connected to local lighting nodes, which then implement adaptive light behavior. This ensures lighting that seamlessly adapts to every phase of the journey – in the terminal, on the aircraft, and during onward transit. It creates a consistent, chronobiologically effective light environment that noticeably enhances well-being throughout the trip. It's a major step toward lighting that truly puts people at the center."

In parallel with technical development, Chronolite focused on scientific validation of the lighting employed. Under the leadership of Charité – Universitätsmedizin Berlin, a controlled laboratory study with healthy subjects examined how dynamically controlled lighting profiles with chronobiological objectives affect key daytime functional parameters such as alertness, concentration, and mood. Special attention was paid to the role of light at specific intensities and color temperatures – mediated by the non-visual receptors in the eye – in regulating circadian processes and cognitive performance. The results are promising – they confirm international studies on the positive effects of dynamic lighting and provide a robust basis for further deployment in transport and everyday life.

The system's usability was also tested with numerous participants. The findings

show that technology which adapts to people gains acceptance – when it is understandable and transparent. Chronolite has demonstrated the feasibility of making chronobiologically effective lighting usable in the mobility context – technically, medically, and from a user perspective. While the system is not yet fully mature, Chronolite sets an important impulse for networked, personalized lighting in mobility.

Further information is available on the project website <https://www.chronolite.de>. The final report has also been published and is available at: <https://doi.org/10.34657/37313>. The project was funded by the Ministry of Transport (https://www.bmv.de/SharedDocs/DE/Artikel/mFUND/KI-Projekt_e/chronolite.html).

Project on Dynamic Lighting for Shift Workers

The project on the effect of dynamic lighting at the workplace for shift workers (Figure 4).

The "Light & Shift" cooperation project investigates short- and long-term effects of modified workplace lighting. Project code: IPA-166-Licht (Parts of this section were taken from Nina Bürger: Effects of Dynamic Lighting on Shift Workers – The 'Light & Shift' Cooperation Project Investigates Short- and Long-Term Effects of Modified Workplace Lighting, Journal 3/2024, 30–33 [in german]:

https://www.dguv.de/medien/ipa/publikationen/ipa-journale/ipa-journale2024/dokumente/ipa_j_03_2024_praxis.pdf).

Light is a primary environmental cue for the internal biological clock. Specific ganglion cells in the eye transmit light signals to a center in the brain, thereby conveying information on the day–night cycle to our circadian clock. This clock controls and synchronizes a multitude of bodily processes that follow a daily rhythm. Long-term disruption of circadian rhythms can have adverse effects on health.

In 2018, the International Agency for Research on Cancer (IARC) classified night shift work as probably carcinogenic. In addition, shift and night work have been associated with a range of other chronic health conditions. A promising approach for prevention of health risks associated with shift work is the design of workplace lighting. In shift workers, usual daily activity patterns – and thus typical daily light exposure profiles – are altered.

With the development of dynamic lighting systems, employers and employees can adjust and optimize individual daylight profiles according to functional, emotional, and biological needs. Although general recommendations for workplace lighting are available, there is a lack of scientific studies and field data for concrete recommendations in shift work.

The preventive approach of the "Light & Shift" intervention study was therefore to

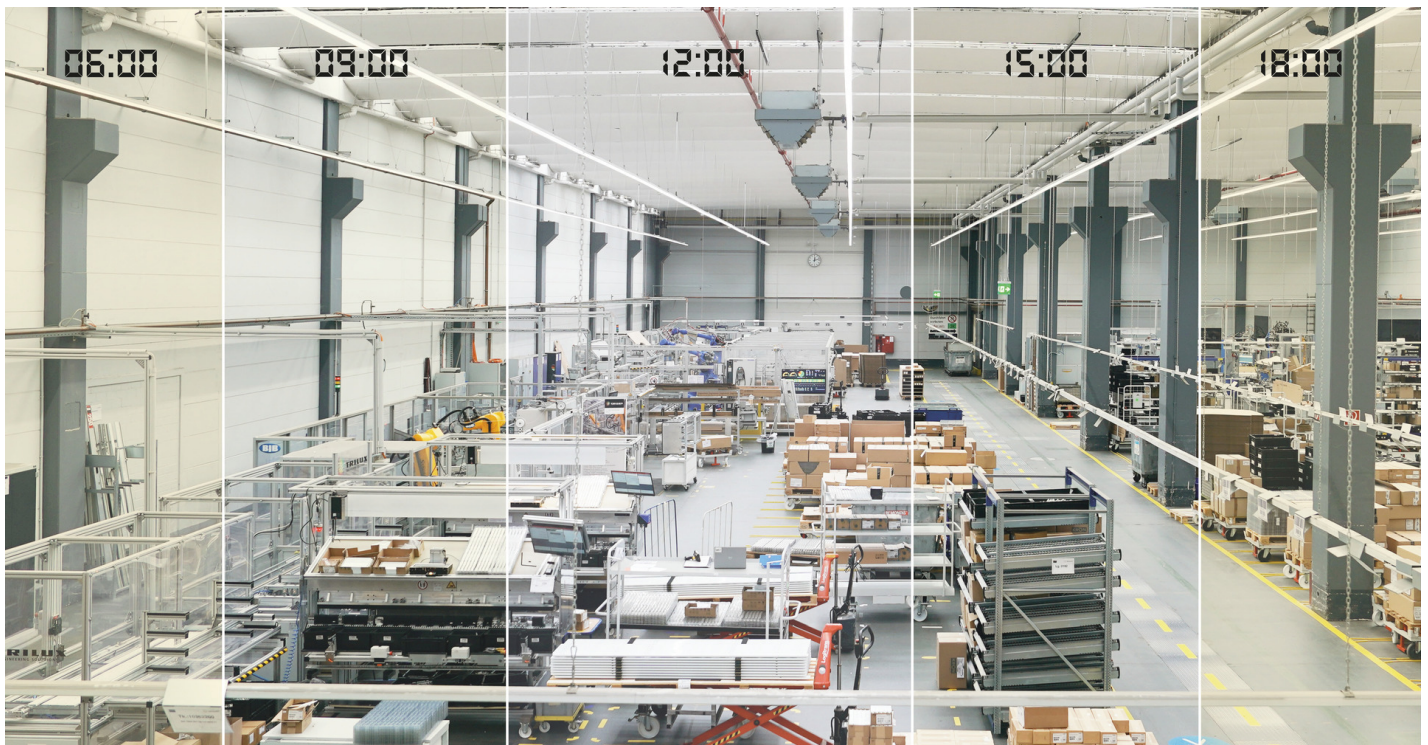


Figure 4: Production hall with circadian lighting scene control.

identify lighting approaches that support shift workers' circadian rhythms. The Institute for Prevention and Occupational Medicine of the German Social Accident Insurance, Institute of the Ruhr University Bochum (IPA), together with the Central Institute for Occupational and Maritime Medicine (ZfAM) in Hamburg and the Technical University Ilmenau, investigated the short- and long-term effects of innovative, dynamic workplace lighting on shift workers. Researchers investigated the short- and long-term effects of dynamic workplace lighting on measurable health parameters such as sleep and hormones in shift workers.

Trilux GmbH & Co. KG participated as an industry partner and provided the opportunity to implement the study in a real-world industrial setting using modern lighting systems. In two production halls, dynamic lighting was introduced for different shifts and maintained over the study period. Over multiple study field phases spanning a period of one and a half years, the research team investigated potential short- and long-term effects on a range of potential health-related outcomes.

Dr. rer. medic. Sylvia Rabstein summarized the current state of knowledge as follows: "The evaluation of the extensive datasets from the 'Light & Shift' study is currently nearing completion. Initial findings suggest that tailored lighting interventions may have a positive effect on selected health-related outcomes. In particular, there are indications that nocturnal light interventions may have favorable effects on sleep duration after the night shift. The final assessment, however, remains subject to completion of the full analysis. At the same time, it is becoming apparent that effects vary depending on the shift system and the specific lighting scenario implemented."

The New Definition of Good Light

Even without normative requirements, current research on HCL and the non-visual effects of light has significantly changed the definition of "good light". "Good light requires more than standard-compliant planning. That's why we have defined the most important quality parameters for good light as we understand it in our lighting philosophy," explains Andreas Picklein, Lighting Application, Academy and Standardization at TRILUX.

THE KEY POINTS:

Good light is ergonomic and pleasant. It must optimally support all visual tasks, avoid glare, and at the same time promote well-being. Dynamic lighting technologies provide the basis for activating and relaxing effects and for supporting the circadian rhythm. Light and luminaires are also design elements that shape spaces in concert with architecture, provide orientation, and highlight functional zones. An intelligent interplay of electric and daylight is essential to ensure optimal quality and sustainability. Good light puts people at the center. In addition to Human Centric Lighting, this includes the ability to adapt lighting to individual needs via lighting management. Cost efficiency and sustainability are also central.

The focus is not only on energy efficiency and luminaire longevity, but also on factors such as efficient use of resources and ease of repair. And of course, good light is characterized by user-friendliness and comprehensive services – with the goal of ensuring ease of use and partnership-based support over the entire lifecycle of the lighting solution. "Despite numerous objective quality criteria, there is no standard recipe for good light. It must always be tailored to the specific on-site conditions and the project-specific wishes of customers. That's why good light is best created through dialogue," adds Andreas Picklein.

To this end, TRILUX offers the industry a wide range of services and touchpoints – from personal consulting and support by lighting and project specialists to physical venues such as showrooms and competence centers. New are the "Light Studios," which TRILUX has just opened in London and Madrid. The concept goes far beyond a classic showroom. With the Sphere of Light as an immersive lighting installation, the space becomes a holistic experience through the interplay of dynamic lighting with media surfaces and sound elements. In addition to demonstration and presentation areas, the Light Studios provide space and infrastructure for workshops and co-creation projects with customers and partners. The closer the collaboration and exchange, the better the outcome can be tailored to the respective requirements. ■

About TRILUX

TRILUX is a leading European provider of professional lighting solutions. Founded in 1912, the family-owned company combines technological expertise, innovative products, and comprehensive services to create intelligent, connected, and sustainable lighting solutions. With a strong focus on people, efficiency, and digitalization, TRILUX supports customers in developing high-quality lighting concepts for offices, industry, retail, and outdoor applications.

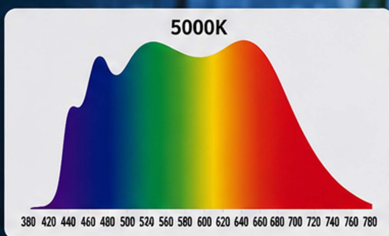
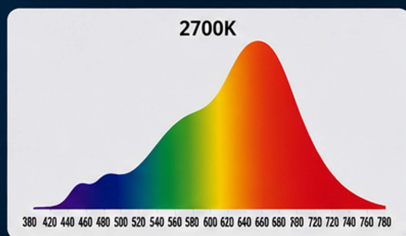


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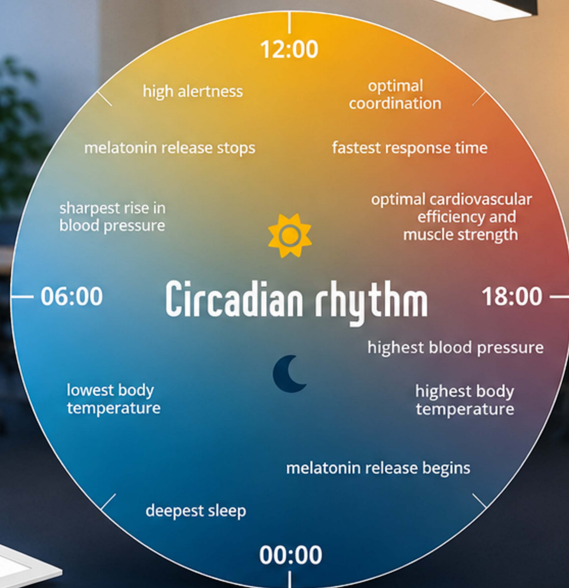
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PREVIEW* Sept/Oct 2026 | LpR 117

Smart City Lighting

LEDprofessional Review (LpR), September/October 2026, will focus on Smart City Lighting and its growing role as the digital backbone of intelligent urban infrastructure. This issue will explore how connected lighting systems, IoT technologies, sensors, AI, edge computing, and open communication standards are transforming street lighting into a multifunctional platform for energy efficiency, public safety, mobility, environmental monitoring, and smart city services. It will highlight the latest developments in adaptive lighting, asset management, cybersecurity, interoperability, digital twins, and data-driven city operations, while examining the integration of lighting with transportation, communication networks, and urban sustainability initiatives. In addition, we will present a curated selection of pioneering projects, innovative technologies, and real-world deployments that demonstrate how smart lighting is enabling the next generation of connected and resilient cities.

* Subject to change without notice.

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Imprint

LEDprofessional Review (LpR)
ISSN 1993-890X

Publishing Company

Luger Research e.U. | © 2001–2026
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