International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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CIE Research Strategy

THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is a global non-profit organization, with the purpose to advance the science, technology and art in the fields of light and lighting. The CIE is recognized as the authority on all aspects of light and lighting. As such it occupies an important position among international organizations. Members of the Commission are National Committees and Associate National Committees, Affiliates and Supportive Members.

The means of the CIE to achieve its purpose, conceptually, are:

1. To provide a forum for diverse open expert discussion and information exchange;
2. To organize scientific and educational events;
3. To hold CIE Sessions and CIE Midterm Meetings;
4. To provide guidance in the application of principles and procedures for the development of international and national standards;
5. To prepare and publish Proceedings, International Standards, Technical Reports, Technical Notes and other publications;
6. To maintain liaisons and technical interactions with other international organizations.

The technical work of the CIE is carried out in its Divisions. This work covers subjects ranging from fundamental matters to all types of lighting applications. CIE technical publications are accepted throughout the world and perceived by their peers as solid and scientifically well-founded.

LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

Les objectifs de la CIE sont :

1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par Comités Techniques, organisés en six Divisions. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.
Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind:

1. Ein internationales Forum für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Messtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird durch Technische Komitees geleistet, die in sechs Divisionen organisiert sind. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind auf der ganzen Welt anerkannt.
Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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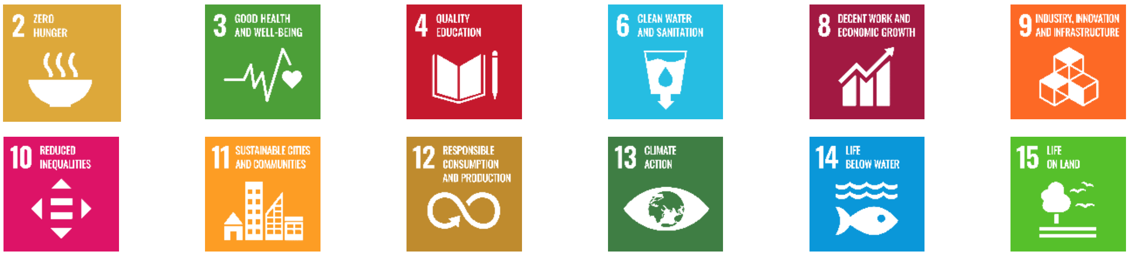
Introduction

The International Commission on Illumination (CIE) is a global non-profit organization dedicated to advancing knowledge and providing standardization to improve the lighted environment. Light and darkness form the fundamental rhythm of daily life for the planet and light reveals the details of the world around us. The CIE seeks to make possible the equitable and responsible provision of the proper light, in the proper place, at the proper time. Doing so is a critical element in humanity's response to global environmental crises including climate change.

Over 1 000 volunteer experts contribute to CIE committees to develop consensus on scientific fundamentals and application guidance that is published in the form of technical notes, technical reports and international standards. Continuing advances in scientific knowledge provide the foundation for new and revised CIE publications. The CIE Research Strategy identifies the topics that researchers should study now, so that the knowledge is available to support and guide the next generation of CIE reports and standards. First published in 2015, the CIE Research Strategy received minor updates in 2019 and 2020. The 2023 edition is a major revision and reflects the CIE's aim to contribute to the achievement of the United Nations 2030 Sustainable Development Goals (SDGs), and specifically those goals whose icons are shown below.



The strategy is organized thematically, with two overarching themes that apply to all research themes and six topical themes describing specific research domains. Throughout the text, the respective SDGs to which each theme will contribute are indicated in parentheses where they are relevant.

Researchers from all areas of science, technology, medicine, psychology, design, information technology, industry, and any allied field can find inspiration in these research themes. The CIE calls on any and all research funders to create opportunities for researchers to address these topics. Light and lighting touch every aspect of life on Earth, and successfully navigating the challenges of today will require the knowledge generated on these themes. Participation in relevant CIE Technical Committees by researchers at any time in the research process should form part of researchers' knowledge mobilization and knowledge transfer plans.

1 Overarching themes

Regardless of the specific topic area, successful accomplishment of the SDGs will require attention to diversity, equity and inclusion, and to the development of advanced digital tools for information and knowledge sharing. These two themes should inform research in all of the specific topical themes that follow.

1.1 Digital transformation of metrology, science, and industry

The 21st century is marked by digitalization of processes, machine learning and artificial intelligence. If used properly, digitalization can contribute to a resilient infrastructure and a better society (SDG 8, SDG 9). Lighting plays an important role in networked systems at the building and city level (SDG 11). Intelligent daylighting controls can reduce energy and resource consumption (SDG 12, SDG 13). The CIE is a signatory to the *Joint Statement of Intent on the digital transformation in the international scientific and quality infrastructure*. By signing this statement, the CIE expresses the importance of adequately supporting these new developments, which it enacts as a member of the International Committee for Weights and Measures (CIPM) Task Group on the Digital SI (CIPM-TG-DSI). The CIPM-TG-DSI will develop and establish a world-wide uniform and secure data exchange format based on the International System of Units (SI), available to everyone (SDG 10). Possible examples of activities are the definition of new data formats; methods to ensure that terms, definitions, and whole standards and technical reports are machine-readable and machine-interpretable; and the provision of reference data sets and evaluation metrics.

To support the digital transformation, the CIE calls upon researchers to do the following:

- collect their data according to internationally accepted data models, and
- report with internationally accepted guidelines, including the FAIR principles, to enable the traceability, comparability and reuse of scientific studies.

In order to generate the best possible benefits, the needs of the stakeholders must be understood and digitalization must occur in cooperation with them. Each of the individual topical themes in the CIE Research Strategy 2023 can contribute to this implementation.

1.2 Towards inclusive, equitable lighting

Research practices have evolved since the early to the mid twentieth century, when the CIE developed its first consensus documents, including one on the spectral luminous efficiency function of the human eye, $V(\lambda)$. At that time, it was common to collect data from a small number of people, including the researchers themselves, and to generalize from this small sample, composed primarily of male Caucasians from North America or Europe, to create an average observer. Then and now, recommendations have been based primarily on delivering adequate conditions for this average observer, with some allowance for changes associated with ageing.

We now recognize, however, that this approach excludes much of the population. Any small sample cannot reflect the full range of characteristics of an entire population, and characterization of the average is likely to misrepresent the central tendency of the whole population by an unknowable amount. As a result, lighting recommendations based on such a limited sample may be unsuitable for the under-represented, meaning that they create an unintended but structural inequity. This inequity can lead to poorer health, safety risks, and poorer quality of life for the excluded individuals and groups.

To prevent the perpetuation of these practices, the CIE recommends the following:

- The CIE calls upon the research community to practice inclusive science by ensuring that when collecting data from people, researchers take care to include a diverse sample – within the appropriate limits of the research question – and to characterize this sample in terms of age, sex or gender, and visual capabilities, adding, where appropriate, cultural identities, personality variables, medical conditions, and special sensitivities (SDG 10).
    - Research replications in another laboratory in another geographic region with a culturally different population would add additional diversity.
    - Specifically, research should include researchers and research participants from countries in the southern hemisphere, and countries that have historically been ignored or that lack research infrastructure. This might require new funding mechanisms to enable the participation of teams from countries that lack research infrastructure
    - Research projects that focus on studying unrepresented groups would add to the knowledge base; examples include neurodiverse individuals, people with varying visual abilities and sensitivities.

The need for greater diversity also extends to other aspects of research design, including settings, tasks, and outcome measures. There is an over-representation of research in office-like settings in the literature. For investigations of daylighting, diversity in geographical location, season, and time of day are important considerations. The inclusion of outcomes spanning a variety of behavioural domains (e.g. physiological measures together with cognitive performance and affective self-reports) in one study can add to the diversity of the knowledge base (SDG 3, 8, 9).

- The CIE recommends that overarching research programmes should incorporate a diverse set of conditions to increase the generalizability of results and to improve their suitability for global applications.
- At the level of individual investigations, researchers should take note of this consideration and moderate their conclusions to the range represented by the study conditions.

Research teams may also lack diversity, despite the fact that more diverse teams lead to more creative results (SDG 10).

- The CIE recommends that all research teams, regardless of the topic, be mindful of equity and diversity in their own composition, actively seeking to include a diverse membership including senior and junior researchers, a mixture of people varying in sex and identity, and varying in other characteristics.

2 Topical themes

2.1 Advances in measurement and calibration

The UN Sustainable Development Goals 8 (Decent work and economic growth) and 12 (Responsible consumption and production) rely upon the international rule-based system of trade, which in turn relies upon international standards of practice. To demonstrate conformity with established rules requires traceable, calibrated measurements of the performance of equipment and systems. As equipment and systems advance, so too must measurement systems. Metrology researchers will also find inspiration in the other topical themes in this document; every lighting investigation rests upon the quality of its physical measurements of light and radiation. The current research gaps are:

- For the past 100 years or more, photometers (light meters) and spectrometers (colour meters) have been calibrated using incandescent lamps. These lamps are easily standardized, and have been cheap, readily available and reliable for a very long time. In recent decades, however, light-emitting diode (LED) light sources have come to dominate the market because of the importance of energy efficiency and their long lifetimes. The production and use of incandescent sources has declined to a point where their availability for scientific purposes has been severely hampered. There is a need for new calibration sources made from LED technology which can replace the incandescent lamps as standard sources. CIE has recently published an LED reference spectrum for photometer calibration (CIE 251:2023), therefore sources can now be designed to realize this reference spectrum, however there still remains a need for continuous spectrum LED sources extending into the UV and NIR for spectroradiometer calibration. This will help to ensure high quality calibrations of testing and measurement equipment so that testing laboratories can verify that products on the market (SDG 8) meet the expectations of consumers and achieve the tasks that they are intended to do (SDG 12).
- Other new light-related devices bring with them measurement needs to ensure they operate as intended and in a safe manner (SDG 12). Examples of applications needing research to establish traceability, metrics, limits and quality indices for new, emerging and alternative devices include measurement of head-up displays, and of augmented reality and virtual reality headsets. Dosimeters for personal exposures to optical radiation are another area of need (see Theme 2.5), as are devices to accurately measure temporal light modulation (TLM) (SDG 3).
- Furthermore, the world is becoming more and more interconnected with detectors that monitor lighting in-situ and report to central control systems for adjusting the light levels and, in some cases, adjusting the nature of the light (for example, tuneable lighting with adjustable correlated colour temperature). Some of these detectors also actively measure the mix of light from electric sources and daylight so that we can optimize the lighting according to the tasks, individual desires, or the time of the day (SDG 12). Moreover, our public infrastructure is becoming increasingly interconnected with sensors controlling devices in applications from transport (trains, intersections, airports) to buildings (heating and cooling, light levels) to public utilities (electricity, gas flow). Specialist applications of this general technology can also include optical systems for telecommunications and medical purposes (SDG 3). Both the sensors and the control systems for them are active areas of research and development.
- Making these systems work as intended requires calibrated sensors, which in a digital world means machine-readable calibration certificates. This will be an essential component of correct operation of complex interoperable systems that manage system conditions, energy consumption, fault detection, and equipment lifetime. Research and development to develop suitable digital measurement and calibration components and to implement these in complex control and building automation systems will be fundamental to achieving smart operation of homes, buildings, and public infrastructure while avoiding excessive resource use (SDG 12).

2.2 Integrative lighting for people

Advances in understanding ocular photoreception have conclusively shown that light influences many physiological and psychological processes in addition to revealing details through vision. *Integrative lighting*, a term added to the International Lighting Vocabulary in 2020, reflects this understanding: "lighting integrating both visual and non-visual effects, and producing physiological and/or psychological benefits upon humans". Present-day guidance on workplace lighting provides good support for health and well-being, but much remains to be known about the effects of light on processes beyond visual performance before comprehensive recommendations and standards can be developed. Examples of high-priority research topics include:

- Light is fundamental to human functioning and well-being, making this research area a key contributor to achieving good health outcomes (SDG 3). This research theme encompasses the full range of psychological and physiological effects of light, from the determination of the necessary daily light-dark pattern of intensity, spectrum, duration and timing for circadian regulation, to the understanding of how the luminous environment can cause discomfort and visual disability, to the importance of beauty in the luminous environment and its effects on well-being. Emerging topics in this area include the potential that optical radiation in the near-infrared range might influence physiology, health and behaviour without ocular photodetection, and the effects of TLM on cognition and neurophysiology. Evidence from this domain can support recommendations for good working environments for worker well-being and their work performance (SDG 8, SDG 9).
- Much of what is known about integrative lighting has come from industrialized countries, often in the temperate latitudes of the northern hemisphere. Achieving inclusion and equity (SDG 10) will be difficult without investigations that span a broader range of locations, climates, cultures, and architectural settings. Similarly, there are gaps in understanding the needs of varying individuals, with few investigations that have examined the needs of other than neurotypical individuals, in a general state of good health, in early adulthood and with light skin colours.
- At present, interior lighting guidance and standards focus on lighting spaces and tasks. Designing lighting for individual needs as well as group needs is likely to be required for fully integrative lighting (SDG 3, SDG 10). This constitutes a a fundamental change in design philosophy and provides a major challenge in lighting design research .
- Daylight is a well-known means for reducing electricity used for lighting and can also contribute substantially to the provision of suitable daily light exposures for health and well-being. Better use of daylight in buildings requires trade-offs with other building services. This particularly includes heating/cooling and ventilation, both to maintain suitable conditions for different sensory systems and also to conserve energy while doing so. Multidisciplinary research combining applied lighting research, the behavioural and health sciences, and other professions and disciplines will be needed to realize the vision of resilient, safe, inclusive and sustainable buildings, cities, and communities (SDG 11) that also use resources responsibly (SDG 12).
- Advances in LED and lighting controls technologies have made dynamic electric lighting installations possible – for instance, electric lighting systems that deliver different light spectra and levels either on a schedule, or on demand – but it remains an open question whether the benefits of using these technologies are sufficient to merit their cost and complexity. The benefits might be different for night-shift workers than for those who work the day shift. Fundamental research can inform us about the need for specific combinations of spectrum, intensity, duration and timing in order to affect desired outcomes; applied lighting research is needed to inform us about the sustainability of these technologies. Furthermore, the consumption of resources during the creation and operation of advanced lighting systems needs to be included within sustainability research to support design choices (SDG 11, SDG 12).

2.3 Ecologically respectful, high-quality exterior lighting

Exterior lighting can be beautiful while also improving safety and security, but it incurs costs, consumes energy (which may cause carbon emissions), can detrimentally affect the natural environment, and obscures the night sky. Lighting of roads and public urban spaces is provided to support safe movement after dark and to create a secure and pleasant atmosphere for outdoor night-time activities. The benefits include reductions in road traffic accidents, improved personal safety, and support for active travel – walking and cycling in particular. Promoting active travel in turn supports healthier lifestyles (SDG 3) and reduces the congestion and pollution associated with motorized vehicles (SDG 11). Balancing the needs of various human observers against environmental considerations requires knowledge across the following topics:

- Light is defined in terms of human vision, but $V(\lambda)$ is not the correct spectral function to apply to plants and animals. To properly balance the needs of the natural world against human requirements, we require more information about the effects of optical radiation on plants and animals, with new SI-compliant quantities and units to provide the foundations of ecologically respectful lighting (SDG 14, SDG 15).
- There is a need to understand how lighting-design criteria should change in order to improve lighting quality in terms of high visual performance, good visual comfort, and where applicable, aesthetic value. Research in this domain should examine observer position, observation angle, types of visual tasks, reflection properties of the illuminated environment, other sources of illumination in the vicinity (including luminous signage), weather conditions, and the numbers and relative velocities of other road users (SDG 3, SDG 11).
- Lighting tailored to actual extrinsic conditions (i.e. traffic situations as well as the demands, needs and preferences of various users) is unthinkable without exploiting sophisticated lighting-control technologies to optimally adapt lighting parameters, and utilization of communication tools to safeguard interoperability of lighting with other services in the framework of “smart city” concepts. Implementation of new advanced technologies such as LiFi, connected vehicle systems, autonomous cars and unmanned aerial vehicles, smart columns, or artificial intelligence is a promising basis for the development of innovative high-tech lighting products, and to establish durable and reliable networks for sustainable infrastructure (SDG 9, SDG 11). Accessibility, energy savings, mitigation of environmental impacts, provision of safe and healthy urban environments are the main targets (SDG 3, SDG 8, SDG 13). High-quality lighting must address the specific needs of people of all ages and abilities (SDG 10).
- Lighting quality is a challenge for outdoor workplaces at night, where the dark background (near-zero background luminance) increases the risk of glare, particularly in combination with a requirement for high light levels on relatively large areas. Outdoor workplace lighting is one of the major light sources influencing the surrounding environment. This creates a challenge to balance the need to improve the labour conditions of workers, particularly shift workers (SDG 8), and the need to prevent unwanted ecological effects (SDG 15). Precise targeting of illumination, adaptive lighting control and avoiding any spill light, are possible general solutions, requiring specific research tailored to different tasks, settings, and locations.
- Although it is well known that excessive use of floodlighting and landscape lighting contribute to obtrusive light problems, less is known about the degree to which problems arise because of intrusive light passing through building envelopes from outside to inside (SDG 3, SDG 11).
- The unwanted consequences of obtrusive light comprise degraded astronomical observations due to sky glow, health effects on people, and the disturbance of habitats of both flora and fauna at the levels of both the individual species and ecosystems. Electric lighting is changing breeding cycles and pollination, behavioural patterns and rhythms, vulnerability to predators, and hormone levels across a broad range of species (plants, insects and animals). Because of the tremendous variety of species, the problem is complex and will require investigations across many locations involving many specialist biologists. As in all topical themes, the key parameters to be studied are the spectrum, intensity, duration, timing and pattern of light exposures (SDG 3, SDG 14, SDG 15).

2.4 Fundamentals of photobiology for agriculture and aquaculture

Interior farming, including aquaculture, is both a mitigation of and an adaptation to climate change, offering the possibility to grow food and raise animals in clean environments, often close to the location where they will be consumed. This can result in improved nutrition for nearby populations, especially in places far distant from more temperate regions (e.g. arctic areas, desert regions) and during winter months in temperate locations, and can reduce the need for long-distance transport from food-producing areas to food-consuming locations (SDG 2, SDG 10). Building indoor agricultural facilities on brownfield lands or in former industrial facilities can reduce the need to disrupt established ecosystems to expand cultivated lands (SDG 12). The success of these endeavours will depend greatly on the successful, energy-efficient, provision of suitable conditions for the plant or animal species inside them, while also considering the need to avoid lighting the night sky. This will require knowledge specific to the intended plant or animal species. Examples of specific research needs are:

- Regardless of whether the animals are indoors all the time or only some of the time, the optical radiation conditions in most animal husbandry facilities differ considerably from the natural environment in which the various animal species (poultry, pigs, cows, sheep, fish, insects, etc.) have evolved. This can compromise animal welfare. A proper specification and evaluation of lighting installations can support visual performance, comfort and welfare in such facilities, balancing the needs of both animals and the humans who care for them. As there is little known about the lighting requirements for the various species, acquiring this knowledge represents a substantial research effort (SDG 14, SDG 15).
- Ultraviolet, visible, and infrared radiation are used in agricultural facilities to promote the rapid and efficient growth of plants and fungi to provide food for us. The nature of the optical radiation to be used changes at different parts of the plants' growth cycle as they may need to grow roots, leaves, flowers and fruit at different times. Optical radiation can also be used to protect plants by discouraging pests, or to facilitate pollination by attracting insects. Plant facilities can also be used to grow plants from seeds to a stage where they can be planted in the wild, to restore plant populations and combat desertification and biodiversity loss. For plants as for animals, we are at the beginning stages of understanding what optical radiation is required for any given species (SDG 14, SDG 15).
- As our knowledge expands in these areas, so too will our need to develop suitable SI-compliant quantities, terminology, measurement protocols, and calibration standards to support agriculture and aquaculture (SDG 9).

2.5 Enabling the application of safe and beneficial optical radiation

Optical radiation covers the range from ultraviolet through visible radiation to infrared and affects myriad biological processes in addition to vision. These processes are important determinants of health and well-being, and research into these effects is expected to result in new standards in the medium to long term.

- The proper light at the proper time is supportive for health and well-being (SDG 3). During daytime, high light levels help to keep us alert and synchronize our internal clocks to the solar day and its seasonal changes. In the evening, the lower light levels signal the end of the day, and at night darkness facilitates a good night's sleep while other restorative processes occur. This much is known, but there remains much uncertainty about how much light exposure, of what spectral composition, for how long, and at what time, is needed, and the correct way to deliver this exposure in an energy-efficient manner.

- The incidence of myopia (near-sightedness) has increased markedly in recent years. Myopia typically emerges during school years and progresses into early adulthood, and increases the risk of blindness and other eye and vision complications in later life. Recent research suggests that exposure to higher light levels during childhood might be protective against the development of myopia, but more detailed evidence is needed to quantify exposures and understand their effects. Given the possible lifetime consequences of inadequate light exposure during childhood, knowledge on this topic is needed urgently (SDG 3).
- Electric light sources with output that varies with time (TLM) can adversely affect visual perceptions, cognition, eye movements, and brain activity. Some individuals are more sensitive to these effects than others, but there remains uncertainty about who is most sensitive and much to be learned about the precise TLM characteristics that cause the greatest problems (SDG 3, SDG 8). Electric lighting is ubiquitous and unavoidable; therefore, it is critical to ensure that, especially in public places, the risk of adverse consequences from unintended TLM exposure is minimized.
- Present-day light sources exclude radiant energy from both the short and the long wavelengths in the optical radiation range, primarily to save energy and partly to reduce risks. Ultraviolet radiation and very intense short-wavelength radiation can lead to adverse actinic effects. These include carcinogenesis, dermal erythema (sunburn) and ocular damage via photokeratitis and the blue light hazard. However, regular low doses of UV-B radiation have the beneficial effect of producing vitamin D in the skin, and there is some evidence for beneficial effects of UV-A exposure on mental states and control of blood pressure. The correct exposure to balance the benefits and risks of actinic radiation is yet unknown. Increased collaboration between medicine, and engineering and lighting application experts would be helpful here (SDG 3).
- Furthermore, UV radiation can be used for sterilization and sanitation, disinfecting air and surfaces from viruses and other pathogens as well as purifying water. Characterizing UV devices and determining how to use them safely in occupied spaces is of interest to improve public health. In turn, increased use of germicidal UV will require improvements to UV radiometry and calibration protocols (SDG 6).
- Near-infrared radiation (NIR) (optical radiation between approximately 780 nm and 1 000 nm) has been excluded from modern light sources because ocular photoreceptors for vision are not sensitive in this wavelength range. Nonetheless, recent studies (including targeted NIR use for medical treatments) have suggested that it might have beneficial biological effects when used in general lighting, possibly through absorption in the skin or tissue (including the eyes). Better understanding of the effects of NIR would expand our knowledge of the proper light and enable the development of lighting and daylighting systems to ensure its application (SDG 3).
- Medical applications of optical radiation are used widely for specific disorders; well-known examples include light therapy for mood disorders and sleep disorders, targeted NIR treatment for wound healing, and the combination psoralen-UVA (PUVA) treatment for skin diseases. Further investigations into the underlying mechanisms could improve treatment efficacy and lead to new treatments for other disorders (SDG 3).
- Researchers seek reliable and well-calibrated light loggers and wearable light dosimeters with tailored spectral and directional sensitivities that account for both visual and other neuroendocrine responses to light (including, but not limited to, circadian regulation). Much remains to be learned about the spectral weighting functions and wearing locations appropriate to different processes, to develop suitable measurement quantities and units, and to build practical devices that will track optical radiation exposures to support well-being and health in the same way as other personal health monitoring devices and platforms (SDG 3). (See also Topical Theme 2.1.)

2.6 Measuring, modelling, perceiving, and reproducing colour

Industry and individuals alike place high importance on the colour appearance of light sources, the materials they illuminate, and displays of all kinds. Characterizing the colour and surface appearance of objects and images contributes to everyday well-being by, for instance, improving image quality in online communications, supporting medical diagnostics, and enabling quality control in manufacturing (SDG 3, SDG 8, SDG 9, SDG 12).

Although colorimetry is generally an established science with commercial instrumentation to measure spectral quantities, there are gaps in our fundamental knowledge and requirements that have arisen because of the development of new technologies, for example solid-state light sources with narrow emission bands. The CIE seeks research input to the definition of metrics, measurement tools, methods and transfer artefacts in order to characterize modern surfaces and to ensure traceability of measurement to the SI, thus supporting quality control and conformity assessment. Specific target areas include:

- Advances in understanding ocular physiology have contributed to the development of cone-fundamental-based CIE colorimetry, but much remains to be learned about the role of the intrinsically photosensitive retinal ganglion cells (ipRGC). Inter-individual variability remains imperfectly understood, especially as it affects observer metamerism, which can be particularly severe with narrowband or spiky spectral power distributions. Understanding variability is a step towards reducing inequality by creating a system that can accommodate different abilities (SDG 10), and supports the Overarching Theme 1.2 for inclusive, equitable lighting.
- The measurement of visual appearance parameters – particularly gloss, texture, translucency, sparkle, and whiteness, and at a greater number of influx/efflux angle geometries than has previously been typical – continues to have a high priority for research (SDG 9, SDG 12). The report CIE 175:2006 remains a good framework for visual appearance measurement research.
- Experts have not agreed which bi-directional reflectance distribution function (BRDF) geometry (size, polarization, shape and uniformity of the illuminated area) would be appropriate for a given sample type (SDG 9). This merits investigation. Furthermore, if a simplified geometry were to be used, then there is a need to quantify the measurement uncertainty.
- When purchasing items online, consumers rely on image display devices to make their choices; they expect that the image they see will be an accurate representation of the item they receive. The translation of colour appearance from a real item to an imaging device and then to a display device is complex, and there are knowledge gaps in the current CIE colour appearance models, for instance with respect to extreme luminance conditions (both very low light levels and very high light levels as seen outdoors on a sunny day) and more complex viewing conditions (existing models are primarily based on simple stimulus configurations). Improving the accuracy of colour reproduction can be expected to reduce the waste that results from consumer disappointment (SDG 12).
- Successful implementations of augmented reality (AR), virtual reality (VR), and extended reality (XR) devices all require visual appearance information for every element displayed (SDG 9). These new technologies would also benefit from data on the real colour gamuts of specific scenes and images. Examples include natural landscapes, food packaging shown together with natural objects, and scenes including light sources.
- 3D printing brings together the challenges of surface colorimetry and colour reproduction. A metrology system is needed for non-uniform 3D objects that brings together the 3D shape, local texture, and the properties that affect visual appearance. Enabling the reproduction of desired shapes, colours, and surface appearance of 3D

objects will be a significant challenge, but is of high interest to industry. Measurement instruments, protocols, and artefacts for calibration also form part of this challenge. Although 3D printing poses particular technical challenges, the effort is justified by the social and environmental benefits of accurate 3D printing. The ability to locally produce items, including spare parts for equipment, on demand, would be far less costly and less wasteful than manufacturing, transporting, and then storing large numbers of possibly unnecessary items (SDG 9, SDG 12).