



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

CIE Research Strategy

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Light and lighting technologies are essential to modern daily life, touching on its every aspect. These technologies require well-founded knowledge, both fundamental and applied, to ensure that they can be used with confidence in their safety and quality. CIE publications provide that confidence. They are based on the strongest available scientific evidence and follow a rigorous review and ballot process. To develop consensus-based documents fit for the future requires that scientists engage now in building the knowledge base that will support them.

The research topics listed here are those judged by the CIE as needing immediate attention by the research community in support of developments in lighting technology and application. Publications in the peer-reviewed literature on these topics will provide the basis for the next generation of CIE technical reports and standards.

Industry, academia, and research institutes alike can take inspiration from this list of research topics. CIE particularly invites allied fields – medicine, engineering, information technology and others – to join with us in addressing these complex questions. CIE calls on national and international research funders to create opportunities that will enable the research community to provide this necessary support to the CIE. Together, we thus will satisfy the needs of industry, regulators, and the public for knowledge, standards, and guidance so that all can enjoy the best possible light.

Top Priority Topics

- [Recommendations for Healthful Lighting and Non-Visual Effects of Light](#)
- [Colour Quality of Light Sources Related to Perception and Preference](#)
- [Integrated Glare Metric for Various Lighting Applications](#)
- [New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry](#)
- [Adaptive, Intelligent and Dynamic Lighting](#)
- [Application of New CIE 2006 Colorimetry](#)
- [Visual Appearance: Perception, Measurement and Metrics](#)
- [Support for Tailored Lighting Recommendations](#)
- [Metrology for Advanced Photometric and Radiometric Devices](#)
- [Reproduction and Measurement of 3D Objects](#)

1 Recommendations for Healthful Lighting and Non-Visual Effects of Light

1.1 Description of research

Although light is defined as electromagnetic radiation that provides the stimulus for vision, we now know conclusively that photodetection also has many other essential physiological and psychological effects in humans and other organisms. Fundamental photobiology research adds to this knowledge base daily. However, targeted research, performed in concert with applied lighting scientists, will be required to put this knowledge to use as part of integrated lighting recommendations and designs.

1.2 Key research questions

In May 2016, CIE published a detailed research agenda for this topic ([CIE 218:2016](#)). Selected examples are given here:

- What pattern of daily light and dark exposure (intensity, spectrum, timing, duration) best supports well-being, both for circadian regulation and acute effects during waking hours (e.g. alertness, emotion, social behaviour)? How does this vary throughout life, from infancy to old age?
- In addition to circadian regulation, what physiological and psychological processes are influenced by ocular light detection?
- There are known medical uses of light to treat certain skin disorders and hyperbilirubinemia. There is speculation that inadequate light exposure during childhood contributes to the development of myopia. These ideas lead to the general question: Are there behavioural or physiological effects of extra-ocular absorption of optical radiation that should influence lighting recommendations?

1.3 Justification of the need for the proposed research topic

- The advances in photobiology and psychology offer the potential to use light exposure both for medical treatment (e.g. phototherapy for mood disorders) and to improve well-being in healthy people. This has excited many people, witness the series of existing CIE publications and current activities on this topic.
- Advances in lighting and controls technologies offer unprecedented opportunities to save energy along with opportunities to enhance health and well-being. A comprehensive research effort will direct the development of these new technologies to the benefit of all.
- Manufacturers are promoting “human centric lighting” at times without a firm scientific basis. As a minimum this means that consumers could be wasting money on ineffective lighting solutions. It might also mean that the lighting could result in adverse effects on health and well-being. Improved knowledge is needed to protect the public and to reduce liability issues for commercial suppliers.
- In parallel, environmental considerations lead to pressure to reduce interior light levels, whether provided by daylight and or electric lighting systems, in order to reduce energy use for both lighting and space conditioning (heating and cooling). This appears to be in opposition to the current knowledge, which suggests that most people receive too little optical radiation each day. Knowledge of dose-response relationships – which themselves demand metrics and devices capable of measuring dose accurately – is needed to resolve this conflict.
- A small number of people experience a range of health conditions due to the spectral emission of light sources or due to the temporal characteristics of light received at the eye. Apart from photo-induced epilepsy, little is known about the triggers for these health conditions. It is important that consideration is given to these issues to ensure that some sectors of the community are not unnecessarily excluded from artificially-lit environments.

1.4 Related current activities in CIE

JTC 4 (D3/D6)	Visual, Health, and Environmental Benefits of Windows in Buildings during Daylight Hours
JTC 9 (D1/D2/D3/D6)	Quantifying ocular radiation input for non-visual photoreceptor stimulation

1.5 Existing CIE publications

CIE 139:2001	The Influence of Daylight and Artificial Light on Diurnal and Seasonal Variations in Humans - A Bibliography
CIE 158:2004/2009	Ocular Lighting Effects on Human Physiology and Behaviour
CIE 218:2016	Research Roadmap for Healthful Interior Lighting Applications
CIE TN 003:2015	Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013
CIE x027:2004	Proceedings of the CIE Symposium 2004 on Light and Health: Non-Visual Effects, 30 Sep.–2 Oct. 2004, Vienna, Austria
CIE x031:2006	Proceedings of the 2nd CIE Expert Symposium "Lighting and Health", 7–8 September 2006, Ottawa, Ontario, Canada
June, 2015	CIE statement on non-visual effects of light: Recommending proper light at the proper time

2 Colour Quality of Light Sources Related to Perception and Preference

2.1 Description of research

With the development of new lighting technologies, LED light sources are increasingly used for general lighting. These light sources are creating diversity in light spectra and imposing new challenges in assessing their colour quality. While a new colour fidelity index is being developed in CIE ([TC 1-90](#)) toward future update of the CIE Colour Rendering Index (CRI), a colour fidelity index alone will not be sufficient to assess the overall colour quality of light sources. Scores of a colour fidelity index do not always agree with perceived colour rendering experienced by end users.

The overall objective of the research topic is to develop indices for colour quality other than colour fidelity, especially those related to general colour preference, which is the perceived or subjective judgement of colour rendering (e.g. for naturalness). It is known that chroma saturation (gamut area) or shift of chromaticity from the Planckian locus has strong effects on perceived colour rendering or preference, but such effects are not measured with a colour fidelity index, and some preferred lights are penalized by a colour fidelity index such as the general colour rendering index, R_a . It seems there are general preferences in chroma saturation and chromaticity, but research data for such perception effects are still very limited. Data are lacking for various conditions, e.g. different hues, different objects viewed, different parameters (naturalness, preference), and long-term effects, in different applications, demographics (race, age, sex), or for different regions of the world. Much more research data are needed to be able to develop an index for perception-based colour quality. A whiteness index also needs to be investigated as a quality index to assess white lights, in order to resolve the problems associated with objects that contain optical brightening agents. Based on the research proposed here, CIE will define standard indices that can be used with a colour fidelity index, all of which will allow specifying or evaluating overall colour quality of lighting products.

2.2 Key research questions

- How can “preference” (or a model for colour quality perception) be clearly defined and assessed for the intended end use? It may also be affected by users’ long term visual experience. How can it be addressed?
- Are the individual variations in such preferences too large to define general preference?
- Can the preference for chroma saturation and white light chromaticity be substantially different in different regions (or race of people) in the world?
- What are the relevant parameters to measure the subjective aspects of colour quality and the whiteness index?
- How to design an index to measure the whiteness perception of a light source? How to apply the surface whiteness indices for lighting application?

2.3 Justification of the need for the proposed research topic

There are many government regulations and voluntary programs to promote energy efficient lighting products. These regulations and specifications not only specify minimum luminous efficacy (lm/W) but also minimum values of the general colour rendering index, R_a , and ranges of white light chromaticity to ensure good colour quality as well as energy efficiency, as both are inter-related. Due to the nature of the CRI (or a colour fidelity index), many preferred lights with increased gamut are excluded when a minimum requirement is given, e.g. $R_a \geq 80$ or $R_a \geq 90$. The colour rendering index drives the manufacturers’ choices of light sources to produce or develop in the future, and thus, has huge impact on the colour quality of lighting products that will be available for general consumers.

Governments are using the CRI (in some cases both R_a and R_9) because only this index is currently available as international recommendation for the assessment of colour quality. In some applications, colour fidelity alone might be suitable, but it may be that in certain applications, colour preference should have a higher priority. Regulations and voluntary programs should be able to use both of these metrics or a combined index so that appropriate colour quality products can be recommended or allowed in different applications. Lights with large gamut areas (which might be more preferred) can be created with spectra containing

narrowband peaks, e.g. RGB (Red, Blue, Green), RGBA (Red, Green, Blue, Amber), or hybrid types, while this can also be achieved by products with any spectra including phosphor white LEDs, having a chromaticity below the Planckian locus. Whiteness evaluation will also be very important in some applications. The use of the CRI (or a new colour fidelity index) alone may mislead or affect future development of new lighting technologies, thus it is critical and urgent to develop colour-preference-related indices and make them available as an international recommendation.

2.4 Related current activities in CIE

TC 1-85	Update CIE Publication 15:2004 Colorimetry
TC 1-90	Colour Fidelity Index
TC 1-91	New Methods for Evaluating the Colour Quality of White-Light Sources
TC 1-95	The Validity of the CIE Whiteness and Tint Equations
DR 1-61	Source Whiteness Metric
DR 1-62	Typical LED Spectra

2.5 Existing CIE publications

CIE 13.3:1995	Method of Measuring and Specifying Colour Rendering of Light Sources
CIE 015:2004 (3rd edition)	Colorimetry (includes the CIE Whiteness Formula and SPDs of many traditional lamps including fluorescent lamps)
CIE 177:2007	Colour Rendering of White LED Light Sources
October, 2015	CIE Position Statement on CRI and Colour Quality Metrics

3 Integrated Glare Metric for Various Lighting Applications

3.1 Description of research

The brightness of light sources, be they electric luminaires or windows, may have a negative effect on the performance of visual tasks (disability glare) but it may also cause a feeling of discomfort without having a directly measurable effect on visibility: discomfort glare. This psychological effect has been extensively studied since the 1940s, when the increase in general illumination levels started to lead to complaints about discomfort from excess light. In general, discomfort is known to increase with increasing luminance of the light source, increasing light source size (at a fixed luminance), decreasing background luminance, and decreasing distance of the bright object from the line of sight. However, discomfort tends to be lower when the light source is daylight rather than when it is electric light. The exact relationship of these quantities has been modelled by various formulae that predict discomfort based on stimulus parameters.

A first drawback of these glare formulae is that each formula is tuned to a set of lighting conditions specific for a given application (e.g. office lighting, sports lighting, road lighting, etc.). Well known examples of such formulae are the Unified Glare Rating (UGR) used for indoor electric lighting systems, the Daylight Glare Probability (DGP) and the Daylight Glare Index (DGI) used for glare from daylight, either through windows or outdoors, and a whole range of discomfort glare metrics, such as the Glare Control Mark, used in outdoor lighting.

A second drawback of such formulae is that they are specific for a type of lighting technology (e.g. luminaires based on fluorescent tubes with an opal exit window, daylight from windows). It is unclear that these formulae provide valid results for light sources other than those used for their development. With the transition to LED lighting, this limitation to specific lighting technologies has become even more problematic. A recent CIE publication ([CIE 205:2013: Review of Lighting Quality Measures for Interior Lighting with LED Lighting Systems](#)) questioned the validity of conventional lighting quality measures for interior lighting with LED lighting systems. The conclusion with respect to glare was that “a new glare evaluation system is needed as the present systems have been developed for circumstances different from LED lighting.”

Thirdly, the glare formulae in current use are based on a fit to empirical data and not based on an underlying physiological or psychological model of discomfort. Because of this it is possible that the glare formulae cannot accurately be extended to situations and lighting technologies that were not used to develop the existing formulae.

CIE recognizes the need for a comprehensive research program to develop a fundamental model of discomfort arising from excessive luminance that will apply to the broad range of applications and technologies.

3.2 Key research questions

- What physiological or psychological mechanism is responsible for discomfort arising from excessive luminance?
- Develop a model of the discomfort arising from excessive luminance, preferably based on parameters that can be related to the discomfort mechanism, which covers multiple application areas.
- Establish a glare metric method that allows the results to be generalized and applied to other application conditions and other lighting technologies.

3.3 Justification of the need for the proposed research topic

The current models for predicting discomfort by glare are all limited to very restricted applications, luminaire characteristics and circumstances. During the past decade many lighting systems with very non-uniform luminance distributions have been introduced. Current glare models are unable to predict discomfort from such sources. Although glare problems have always been seen as relevant to lighting design but difficult to quantify, they have been thought to be too difficult to include in recommendations for most applications. With the metrics that are used now, discomfort that may be caused by many modern products is over- or underrated. Being able to predict discomfort arising from glare will be beneficial to end

users because it will enable its prevention. Manufacturers will be better able to develop suitable products and to categorize the suitability of their products for various configurations and applications. This will facilitate better choices by lighting designers and specifiers. A single glare model covering as many as possible applications will mean an important simplification from the current situation with 20+ models and will allow cross-learning between application areas, which will help to build our understanding of lighting quality and comfort.

3.4 Related current activities in CIE

TC 3-53	Revision of CIE S 008 Joint ISO/CIE Standard: Lighting of Work Places - Part 1: Indoor
TC 3-56	Assessment of Discomfort Glare from Daylight in Buildings
TC 4-33	Discomfort Glare in Road Lighting
JTC 7 (D3/D1)	Discomfort caused by glare from luminaires with a non-uniform source luminance

3.5 Existing CIE publications

CIE 31-1976	Glare and Uniformity in Road Lighting Installations
CIE 55-1983	Discomfort glare in the interior working environment
CIE 112-1994	Glare evaluation system for use within outdoor sports and area lighting
CIE 117-1995	Discomfort glare in interior lighting
CIE 146-2002/ CIE 147-2002	CIE collection on glare
CIE 205:2013	Review of Lighting Quality Measures for Interior Lighting with LED Lighting Systems
CIE 213:2014	Guide to protocols for describing lighting

4 New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry

4.1 Description of research

In photometry and radiometry appropriate calibration sources and transfer detectors are necessary to ensure traceability of measurements. In addition, calibration conditions should be chosen as close as possible to the measurement conditions. Incandescent lamps have been used for such calibrations for decades, but their availability is diminishing. LED-based standards would bring several benefits for calibration laboratories, photometer manufacturers, and for those using instruments for measurement of white LED lighting. However, different types of LED-based standards have to be considered in general:

- LED standards to realize the lamp based quantities to define and disseminate the units for luminous intensity, luminous flux and luminance. These are the highest precision devices which have to cover at least the whole visible spectral range from 360 nm to 830 nm defined by $V(\lambda)$, $V'(\lambda)$ and $V_{\text{mes},m}(\lambda)$.
- LED standards for the dissemination of the photometric units with properties close to typical LED lamps, modules and luminaires used in applications. These standards are typically based on coloured or white LEDs, not necessarily covering the whole spectral range of the visible spectrum.
- LED standards can be used for the general characterization of measurement setups used in test laboratories. These standards are used to reduce the uncertainties encountered by test laboratories in measurements of general purpose luminaires.

In the case of LED standards for the dissemination of photometric units for white LEDs, some drawbacks must be considered, in particular the fact that there is not a single spectral power distribution that would be representative of white LED sources. Thus, it may be necessary to consider a family of standard LED illuminants to represent these different applications. This is a similar principle to what has been done in standardizing lamp spectra F1 to F12 of fluorescent lamps (CIE 015:2004), where selected spectral distributions of different lamp designs are specified.

Finally, research is needed for calibration sources for spectral quantities in extended wavelength ranges (UV to NIR) as replacement of existing halogen-based sources. Different possibilities could be considered, including new LED sources, laser-driven light sources, white-light laser sources, and tuneable laser sources (for detector-based calibration).

4.2 Key research questions

- What spectral range is necessary for LED standard sources and what composition of LEDs should be used to realize such a standard?
- What would be the best reference spectrum (spectra) based on LED products for general-purpose white lighting LEDs, considering that these products are still in evolution?
- What are the alternative sources to calibrate spectroradiometers over extended wavelength ranges, including NIR and UV?
- What are the impacts due to the changes to new calibration sources and in the definition of new (standard) illuminant(s)?

4.3 Justification of the need for the proposed research topic

A good metrological system relies on the availability of stable light sources and detectors. A major challenge is the technological revolution of lighting products towards LED lighting and the ban of incandescent lamps. This raises concern about the availability of incandescent photometric standard lamps in the future. The prices of such standard lamps are already increasing, and acquiring some lamp types has become increasingly difficult. Therefore, it is important to investigate the pros and cons of replacement of conventional standard lamps with new solid-state technology.

Metrology using LED-based devices is much more complex than it was using the former, incandescent-based, technology. Uncertainties originating from the operating parameters, spectral distribution and spatial properties are frequently underestimated. Appropriate

standards together with improved measurement devices (Research Topic "[Metrology for Advanced Photometric and Radiometric Devices](#)") are a basic prerequisite and fundamental to facilitate future smart and adaptive lighting technologies and applications.

4.4 Related current activities in CIE

TC 2-87	Broadband UV LED radiometric measurements between 320 nm and 420 nm
DR 2-71	Towards LED based standard calibration sources for photometry
DR 2-58	Standard lamps: availability of and alternatives to commercially available incandescent sources

4.5 Existing CIE publications

CIE 149:2002	The Use of Tungsten Filament Lamps as Secondary Standard Sources
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5 Adaptive, Intelligent and Dynamic Lighting

5.1 Description of research

With the advent of advanced control systems incorporating LED sources, the opportunity to provide fully adaptable lighting is a significant direction being considered by industry. The term adaptive lighting refers to the changing of the light source condition, whether overall level, colour, light distributions or some other metric based on the needs of the environment. The adaptability of a lighting system can be classified into four levels:

- Level 1 – Adaptation using time schedules based on statistics
- Level 2 – Adaptation on demand using local sensors or individual local controls
- Level 3 – Adaptation with links to intelligent systems such as building automation systems (BAS) and intelligent transport systems (ITS) on selected roadways
- Level 4 – Adaptation combining the options of Levels 2 and 3, for example:
 - Scheduled changes in light source colour or level to mimic daylight patterns, with or without local occupancy detection, task tuning, or daylight-harvesting
 - Adaptation with links to ITS systems on all roadways with electrical and lighting management systems (ELMS) control
 - Luminance monitoring
 - Lighting-on-demand – lights that are activated by immediate need and otherwise dimmed or off, e.g. with Connected Vehicle Technology or in response to local occupancy signals
 - Smart city and smart building applications

At this point, while the technology exists to provide all of these capabilities, the application and usability of these adaptive approaches has not been considered. In this topic, we promote the consideration of user needs together with environmental considerations and energy usage.

5.2 Key research questions

- What is the impact of adaptive lighting on user behaviour or reactions, such as occupants' space perception or driver safety?
- How should the system adapt itself to the circumstances to provide the optimal lighting? For example:
 - Could the system detect individual needs for varying visual conditions?
 - Could roadway lighting vary depending on traffic composition, traffic density, and weather conditions?
- What are the relations between lighting settings and user safety and comfort?
- Which types and levels of dynamics are acceptable in a lighting installation?
- Which types of input and feedback (e.g. road surface luminance monitoring, photocells, presence detection, algorithms for integrated multi-sensor input, automated fault detection) are necessary to ensure system usability?
- What are the energy and operational costs and benefits of adaptive lighting?
- Could adaptive exterior lighting have ecological benefits beyond energy savings?

5.3 Justification of the need for the proposed research topic

The potential benefits of an adaptive lighting system (sometimes called “smart lighting”) are significant. There is the possibility for a significant reduction in energy usage, sky glow, light trespass and maintenance costs while still maintaining user safety. Furthermore, the energy benefits of adaptive lighting can be used to ensure that energy code limits on installed lighting power density do not restrict the ability to deliver the quality and quantity of light when needed.

The technology to provide adaptive lighting is already in the marketplace and being accepted by some jurisdictions. The proper use of these technologies however has not been identified,

so that there remains a risk that some applications might adversely affect users. In order to ensure that no harm is done with the application of these systems there is a significant need to answer these research questions.

5.4 Related current activities in CIE

TC 3-49	Decision Scheme for Lighting Controls for Tertiary Lighting in Buildings
TC 4-51	Optimization of Road Lighting
TC 4-52	Lighting for Pedestrians: New Empirical Data

5.5 Existing CIE publications

CIE 115:2010	Lighting of Roads for Motor and Pedestrian Traffic
CIE 205:2013	Review of Lighting Quality Measures for Interior Lighting with LED Lighting Systems

6 Application of CIE 2015 Cone-Fundamental-Based CIE Colorimetry

6.1 Description of research

Since colorimetry was established in 1931, considerable improvements in the metrology of the colour stimulus and immense advances in the knowledge of colour vision have been made. Based on the modern knowledge of the human colour visual system CIE published a set of new colour-matching functions that takes into consideration the age of the observer and the field size of the stimulus, and provides a method to derive the associated chromaticity diagram (see [CIE 170-2:2015](#)).

The objective of this research is to conduct field trials that compare the results of the use of the CIE 1931 (2°), CIE 1964 (10°) and CIE 2015 cone-fundamental-based colour-matching functions, especially when applied to LED lighting and in imaging applications. Also the method to be used to calculate the CIE 2015 cone-fundamental-based colour-matching functions needs to be standardized.

6.2 Key research questions

- How accurate are cone-fundamental-based colorimetry results compared with those of 1931 and 1964 in predicting typical colorimetry applications such as colour difference, colour appearance, whiteness, colour rendering, etc.?
- Can the cone-fundamental-based colorimetry be used to quantify the age metamerism effect and the size metamerism effect? There is an urgent need to quantify observer metamerism. Evidence suggests that the earlier CIE method underestimates these effects.

6.3 Justification of the need for the proposed research topic

It is occasionally experienced that object colours do not visually match though the colorimetric values are the same. There is strong evidence that there can be significant errors in the current colour specification using the CIE 1931 standard colorimetric observer applied to typical white LED light sources. The CIE 1931 colorimetric system needs to be improved possibly by adopting the CIE 2015 cone-fundamental-based colorimetric system for the calculation of colorimetric parameters to be used for the computation of lighting quality data. Therefore, intensive field trials are required to help the colour, imaging and lighting industries to have confidence that CIE 2015 cone-fundamental-based colorimetry is fit for their use.

The CIE 2015 cone-fundamental-based colorimetry has established a link between colorimetry and physiology. This link will improve the understanding of colour, will be useful for education and will offer novel opportunities to solve problems of colour measurement and colour perception in everyday life and industry.

6.4 Related current activities in CIE

TC 1-93	Calculation of Self-Luminous Neutral Scale
TC 1-97	Age- and Field-Size-Parameterised Calculation of Cone-Fundamental-Based Spectral Tristimulus Values
JTC 9 (D1/D2/D3/D6)	Quantifying ocular radiation input for non-visual photoreceptor stimulation

6.5 Existing CIE publications

CIE 170-1:2006	Fundamental Chromaticity Diagram with Physiological Axes - Part 1
CIE 170-2:2015	Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams

7 Visual Appearance: Perception, Measurement and Metrics

7.1 Description of research

The overall objective of this research topic is to define metrics describing the appearance of various materials in order to support relevant stakeholders (e.g. the automotive, cosmetics, paper, printing, coatings, plastics industry, etc.). In addition to the definition of a metric, measurement tools, methods and transfer artefacts shall be provided, in order to characterize modern surfaces and to ensure traceability of measurement to the SI and a reliable and well-managed visual and instrumental correlation.

Colorimetry is based on the measurement of spectral reflectance or transmittance, and, in general, is an established science that is possible using commercial instrumentation available at reasonable cost. Two shortcomings, however, are identified: First, there are a number of modern materials where colour measurements made by using a single pair of influx/efflux geometries is not sufficient to describe the perceived colorimetric effect. Thus, measurement at more influx/efflux angle combinations is required. Second, the traditional CIE-recommended colorimetric parameters, while providing correlates of visual percepts, are not able to predict the absolute appearance of a coloured sample under various conditions; colour appearance models are now able to do this.

The scientific and technical objectives of this research topic are to investigate advances in the measurement of appearance parameters including gloss, texture, whiteness and goniometric techniques. A more detailed description of the framework for the measurement of visual appearance is given in CIE 175:2006.

7.2 Key research questions

- What are the relevant parameters to describe appearance, gloss and translucency of various materials, including goniochromatic and sparkling samples?
- Which BRDF geometry (size, polarization, shape and uniformity of the illuminated area) according to the type of sample under investigation shall be standardized?
- If a simplified geometry is used as a standardized description of effect materials, how can the “uncertainty” with respect to the real visual appearance, i.e. the proficiency of the test method, be described?

7.3 Justification of the need for the proposed research topic

Visual appearance is one of the most critical parameters affecting customer choice and needs in products; therefore it should be quantifiable to ensure uniformity and reproducibility. The industry will directly benefit from:

- Improved measurement technology - leading to better quality control:
Research will highlight the critical parameters in the design and use of measurement devices used to quantify the appearance of an object. The goal is to understand some of the problems, to provide a framework describing the relationships between the various proposed measurement parameters, and to encourage others to contribute the findings of their research to the knowledge base that will support the framework.
- Access to and support of measurement traceability:
Success in defining new measurement scales can be enhanced by understanding all the aspects that influence the measurement, and quantify their contributions to the measurement uncertainty. Once a primary scale is established, traceability of industry-based measurement systems is possible.

7.4 Related current activities in CIE

TC 1-95	The Validity of the CIE Whiteness and Tint Equations
TC 2-85	Recommendation on the geometrical parameters for the measurement of the Bidirectional Reflectance Distribution Function (BRDF)
TC 8-14	Specification of Spatio-Chromatic Complexity
DR 1-53	Gloss Perception and Measurement
DR 2-64	Technical Note on Errors of Measurement in Spectrophotometry
DR 2-74	Physical characterisation of new visual effects in the field of appearance of materials

7.5 Existing CIE publications

CIE 038-1977	Radiometric and Photometric Characteristics of Materials and their Measurement
CIE 044-1979	Absolute Methods for Reflection Measurements
CIE 046-1979	A Review of Publications on Properties and Reflection Values of Material Reflection Standards
CIE 054.2-2001	Retroreflection: Definition and Measurement
CIE 076-1988	Intercomparison of Measurements of (Total) Spectral Radiance Factor of Luminescent Specimens
CIE 130-1998	Practical Methods for the Measurement of Reflectance and Transmittance
CIE 175:2006	A Framework for the Measurement of Visual Appearance
CIE 176:2006	Geometric Tolerances for Colour Measurements
CIE 182:2007	Calibration Methods and Photoluminescent Standards for Total Radiance Factor Measurements

8 Support for Tailored Lighting Recommendations

8.1 Description of research

Individuals differ widely in visual capabilities and needs. Lighting recommendations are based on average results, usually for able-bodied young adults. A concerted research effort is required to deliver knowledge that can support specific lighting recommendations for specific populations. Two groups of particular interest are the elderly (a demographic group known to be increasing as a proportion of the population in most countries) and those with visual impairments. Other groups of special interest are those susceptible to migraine headache, epilepsy, and depression. Research in this field could lead to modifications to recommendations to aid these populations. With better knowledge, modifiers could be applied to any lighting recommendation to provide for the needs of identified groups.

In a related vein, there is evidence that lighting recommendations could be made conditional in order to provide guidance that balances different concerns. For example, high colour fidelity may improve visual performance such that illuminance levels could be reduced. This could be of benefit to those with colour vision deficiencies, as well as offering the opportunity to reduce lighting energy use.

8.2 Key research questions

- What are the age-related changes in non-visual photoreceptors (ipRGC) and neural responses? How does this change lighting recommendations for the elderly?
- Which ageing effects of the visual system are most detrimental to the performance of workers, drivers and pedestrians and how could or should this be taken into account in lighting design and requirements?
- How do visual impairments or disabilities affect the performance of people and how should these be taken into account in lighting design?

8.3 Justification of the need for the proposed research topic

Globally, the proportion of older people is increasing, which brings into question the suitability of lighting recommendations based primarily on research with younger populations. Although there is good knowledge of the visual changes that occur with age, such as diminished visual acuity and increased susceptibility to disability glare, there is far less known about how to adapt lighting design and recommendations to the visual needs of those with specific visual impairments. The knowledge generated under this topic would lead to benefits for segments of society that are not well served by current recommendations, including the elderly, those with visual impairments, and those with special sensitivities. It would be expected to drive technological change by providing the evidence needed for the development of suitable lighting technologies or design practices to assist these populations.

The potential beneficiaries of this work are many. For example, there is some evidence that certain individuals are more susceptible to spatial and temporal patterns of light and are at risk of headache, eyestrain, and visual disturbance as a result, but there are no specific lighting design recommendations for these individuals and no validated method for identifying those who might need this assistance. However, any recommendations from the research should also consider the impact on the wider population who might not need this assistance.

8.4 Related current activities in CIE

TC 1-83	Visual Aspects of Time-Modulated Lighting Systems
TC 1-84	Definition of Visual Field for Conspicuity
TC 1-89	Enhancement of Images for Colour Defective Observers
TC 3-44	Lighting for Older People and People with Visual Impairment in Buildings
TC 4-54 (in the course of formation)	Road Lighting for Ageing Drivers
DR 1-66	The Effect of Dynamic and Stereo Visual Images on Human Health
DR 4-41	Lighting for the Elderly and Visually Impaired

8.5 Existing CIE publications

CIE 196:2011	CIE Guide to Increasing Accessibility in Light and Lighting
CIE 218:2016	Research Roadmap for Healthful Interior Lighting Applications

9 Metrology for Advanced Photometric and Radiometric Devices

9.1 Description of research

In the past CIE has published technical reports and standards defining procedures for characterization, calibration and testing of photometric and radiometric devices and measurement systems such as illuminance meters, luminance meters, integrating spheres and goniophotometers. Due to technological progress new types of photometric and radiometric measurement devices have appeared on the market, including

- imaging luminance measurement devices (ILMDs) and hyperspectral measurement devices (spectrally resolved ILMDs);
- LED-based spectrophotometers;
- imaging luminance-based near-field goniophotometers;
- gonio-spectroradiometers and sphere-spectroradiometers;
- robot-goniophotometers;
- imaging sphere photometers;
- combined measurement devices using spectroradiometers and broadband measurement devices;
- high-speed measurement systems to quantify fast-varying (pulsing, modulating, flickering) optical signals, etc.;
- measurement devices for quantifying photochemical and photobiological (including non-visual) effects.

For some of these devices new CIE technical committees have been established and others are to follow. However, in most cases additional research is still necessary and the period of time allowed to finalize a report or standard is often too short. In spite of this, there is an immediate need to define quality criteria and calibration procedures for devices such as near-field goniophotometers and array spectroradiometers, as such devices are becoming more widely used in practice. Hence, it becomes urgent not only to participate in a technical committee to offer knowledge but also to offer practical research on the open topics to feed in to the technical committees. Having more research groups operating in parallel can enable a technical committee to perform its work more efficiently.

9.2 Key research questions

- What are the relevant quality indices to characterize advanced photometric and radiometric devices? How do these indices relate to the measurement uncertainty in typical lighting measurement situations?
- How to describe the measurement equations describing the measurement procedure?
- What would a standard measurement uncertainty budget look like for measurements on particular types of equipment?
- How to calibrate these new types of devices? What are the best artefacts to transfer the photometric quantities to the measurement device?
- How to assess temporal exposures of the eye from sources that may flicker (up to about 1 kHz) or where the source and observer move in relation to each other generating a temporally-changing exposure at the eye?
- How can these topics be divided into different parallel threads to improve the efficiency of the respective TCs?

9.3 Justification of the need for the proposed research topic

New challenges like “smart lighting” (i.e. adaptive and sensor-based lighting) and the implementation of the other research topics within the CIE Research Strategy priority list imply on the one hand the need to completely characterize a given lighting situation, including daylight and artificial light from various sources, and on the other hand to thoroughly characterize the used light sources or luminaires with respect to spectral and spatial properties. Absolute traceability of measurement results is mandatory to combine such

source-based and detector-based measurements under various environmental conditions. New devices and measurement systems as described above are needed to meet these challenges. The outcome of this research will increase the quality of photometric and radiometric measurements in general and therefore increase confidence in lighting products. The availability of reliable and traceable measurements is also a prerequisite to develop and verify intelligent sensor systems used to enable smart and adaptive lighting.

9.4 Related current activities in CIE

TC 2-29	Measurement of Detector Linearity
TC 2-59	Characterisation of Imaging Luminance Measurement Devices
TC 2-62	Imaging-Photometer-Based Near-Field Goniophotometry
TC 2-69	CIE Classification Systems of Illuminance and Luminance Meters
TC 2-74	Goniospectroradiometry of Optical Radiation Sources
TC 2-78	The Goniophotometry of Lamps and Luminaires
TC 2-79	Integrating Sphere Photometry and Spectroradiometry
JTC 5 (CIE-IEC)	Review of IEC 62471/CIE S009
DR 2-69	TN on the validation of a near-field goniophotometer
DR 2-57	Monitoring Progress of IEC TR 62778

9.5 Existing CIE publications

CIE 053-1982	Methods of Characterizing the Performance of Radiometers and Photometers
CIE 063-1984	The Spectroradiometric Measurement of Light Sources
5TCIE 084-1989	Measurement of Luminous Flux
CIE 121-1996	The Photometry and Goniophotometry of Luminaire
CIE 179:2007	Methods for characterising tristimulus colorimeters for measuring the colour of light
CIE 198:2011	Determination of Measurement Uncertainties in Photometry
CIE 198-SP1:2011	Determination of Measurement Uncertainties in Photometry - Supplement 1: Modules and Examples for the Determination of Measurement Uncertainties
CIE 202:2011	Spectral Responsivity Measurement of Detectors, Radiometers and Photometers
CIE 210:2014	Photometry Using V(λ)-Corrected Detectors as Reference and Transfer Standards
ISO/CIE 19476:2011	Characterization of the Performance of Illuminance Meters and Luminance Meters

10 Reproduction and Measurement of 3D Objects

10.1 Description of research

3D printing technology, also known as additive manufacturing technology, is one of the most revolutionary technologies in recent years. The materials used in the process are not just limited to polymers but also metals and biological tissues, and maybe their combination in the future. This technology is used for quick prototyping, manufacturing complex 3D parts, prostheses, educational training objects and even prefabrication of housing. As compared with 2D reproduction, 3D reproduction needs to satisfy more requirements for visual attributes such as surface colour, translucent colour, bidirectional reflectance distribution function (BRDF), gloss and texture on both curved and flat surfaces. The relationship between desired 3D objects in the design process and produced 3D objects must be visually and quantitatively assessed. Characterization of the colour appearance of 3D objects requires a design software with the ability to capture both the physical properties of the materials and the visual adaption properties of the observations. This aspect will be associated with the appearance without constraints on the observing conditions.

These challenges will not be solved sufficiently by simple extension of technologies developed for 2D colour image reproduction and measurement. However, some printer makers are already describing the outputs as CMYK printing, even though there are no halftones in the printed objects. New scientific models and new engineering ideas will be necessary to give feasible analysis and practical implementation of 3D-printed coloured objects. Moreover, the final property of a 3D-printed object will have some deviations from the properties designed, thus a 3D-object proofing system will be necessary analogous to a colour-proofing system in conventional printing.

The research will be divided into three steps: input, processing and output. The input step is mainly to measure and design the characteristics for both targeted and reproduced objects. In addition to the measurement of the spatial dimensions, appearance such as colour, texture, reflection of the 3D objects must be measured and characterized. In the processing step, the input data should be analysed and reduced into a smaller number of parameters by simple or comprehensive models that convert the images into mechanical drawings for easy handling. Such parametric reformatting will contribute to the reproduction industry so as to improve efficiency in the manufacturing of the parts. The output step covers the realization of the targeted shape, with the required colour, appearance and texture attributes as designed. These attributes will be compared with the ones of the original in the input step again. Objective assessment is required for quality control in the complete industrial or medical chain from the designer to the consumer. There are many opportunities to tackle these issues.

10.2 Key research questions

- To develop the metrology of non-uniform 3D objects, including the 3D shape, the local roughness, the texture aspect and other properties impacting on the visual aspect.
- New ideas for measurement instruments and their realization for the aspect above.
- To define a set of metrological distance/similarity metrics between two objects embedding the set of differences in 3D shape, colour, texture, and surface morphology.
- How to make a simple or comprehensive surface model including the physical and visual characteristics to develop the market and industry of 3D-numerical objects.
- How to reproduce the desired shape, colour, appearance and texture, especially when the target surface has translucent characteristics. This will be a major challenge since this problem has yet to be fully solved even for 2D materials.

10.3 Justification of the need for the proposed research topic

- Technical and metrological benefits:
 - By modelling attributes of 3D objects, clearer understanding of the surface attributes will be obtained. The model and measurement guideline will lead to more accurate reproduction and evaluation.

- A new type of measurement instrument needs to be specified since the target is not limited to flat objects. This measurement technology could be utilized for any flexible devices such as OLED lighting and display systems.
- Research development and innovation:
 - Measurement instruments for 3D objects would be based on 2D imagers because of the necessity of measurement of small continuous areas on a curved surface.
 - Such instruments for 3D objects will be utilized for evaluation of any non-flat surface as e.g. in automobile painting.
- Social and environmental benefits:
 - By supporting the accurate reproduction of 3D printing, there is opportunity to create a new and significant market.
 - Currently vendors need to hold a large number of inventories of mass produced replacement parts, but in the future, 3D printing technology would manufacture the parts on demand. Possible environmental benefit is to reduce inventory of spare and maintenance parts by industry.

10.4 Related current activities in CIE

TC 2-85	Recommendation on the geometrical parameters for the measurement of the Bidirectional Reflectance Distribution Function (BRDF)
TC 8-14	Specification of Spatio-Chromatic Complexity

10.5 Existing CIE publications

Report of DR 8-11 (only internally available)	Colour image reproduction for 3D printing
Report of DR 8-12 (only internally available)	3D Multi-view Image/Video Colour Data Format Conversion and Quality Control