Texte zu den geplanten neuen EU-Regelungen zur umweltgerechten Produktgestaltung und zur Energieverbrauchskennzeichnung in der Beleuchtung – Zusammenstellung [1] des Umweltbundesamtes (UBA), Deutschland

Gesundheit

Hintergrundtext:

SCHEER-Stellungnahme [2] zu möglichen Risiken für die menschliche Gesundheit durch Leuchtdioden (LED)

– SCHEER-Entwurf vom 6. Juli 2017 –

Hinweis: Bitte beachten Sie, daß der angehängte Text nur in Englisch verfaßt ist.

EN: Information on the coming EU Lighting Regulations – Ecodesign and Energy Labelling – Compilation [1] of the Federal Environment Agency (UBA), Germany

Health

Background information: SCHEER [2] Opinion on Potential risks to human health of Light Emitting Diodes (LED)

– SCHEER's Draft of 6 July 2017 –

FR: Informations sur les futures réglementations de l'UE concernant l'éclairage – l'écoconception et l'étiquetage énergétique – Compilation [1] de l'Agence Fédérale de l'Environnement (UBA), Allemagne

Santé

Informations de fond : Avis du SCHEER [2] sur les risques potentiels pour la santé humaine par diodes électroluminescentes (DEL)

– Projet de SCHEER du 6 juillet 2017 –

Indication : Veuillez noter que le présent texte n'est disponible qu'en anglais.

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[1] https://www.eup-network.de/de/eup-netzwerk-deutschland/offenes-forum-eu-regelungen-beleuchtung/dokumente/texte/

[2] SCHEER = Scientific Committee on Health, Environmental and Emerging Risks ◊ **DE**: Wissenschaftlicher Ausschuß für Gesundheits-, Umwelt- und aufkommende Risiken ◊ **FR** : Comité scientifique sur la santé, l'environnement et les risques émergents I https://ec.europa.eu/health/scientific_committees/scheer_en

DE: ↓ **EN**: → page III **FR** : → page IV

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      - Änderungen in der Endfassung vom Juni 2018 gegenüber dem Entwurf vom Juli 2017 *
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      - Stellungnahme lichtfragen.info (20. August 2018) [DE] [EN]
  - Produkteigenschaften
  - Sonstige

* Stand: 17 .8. 2018: Dieser Text ist noch nicht verfügbar.

Abkürzungen: • • SCHEER: Wissenschaftlicher Ausschuß für Gesundheits-, Umwelt- und aufkommende Risiken; https://ec.europa.eu/health/scientific_committees/scheer_en

EN

Documents in the Open Forum and identification of the text at hand

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    - **Documents of the SCHEER Committee**
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* Status as of 17 August 2018: This text is not yet available.

Abbreviations: • SCHEER = Scientific Committee on Health, Environmental and Emerging Risks; https://ec.europa.eu/health/scientific_committees/scheer_en

FR

Documents dans le forum ouvert et marquage du présent document

- **Règlements existants de la CE et de l'EU**
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- **Projets de règlements**
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    - Commentaires
      - Commentaires par lichtfragen.info (20 août 2018) [DE] [EN]
  - Caractéristiques du produit
  - Autres

* État au 17 août 2018 : Ce texte n'est pas encore disponible.

Abréviations : • SCHEER : Comité scientifique sur la santé, l'environnement et les risques émergents; https://ec.europa.eu/health/scientific_committees/scheer_en

Es folgt ein unveränderter Originaltext.

EN: The following is an unmodified original text.

FR: Ce qui suit est un texte original.

Scientific Committee on Health, Environmental and Emerging Risks

SCHEER

Preliminary Opinion on

Potential risks to human health of Light Emitting Diodes (LEDs)

The SCHEER adopted this Opinion by written procedure on 6 July 2017

ABSTRACT

Following a request from the European Commission, the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) reviewed recent evidence to assess potential risks to human health of Light Emitting Diodes (LEDs) emissions.

The review of the published research conducted by the SCHEER has led to valuable conclusions and identified certain gaps in knowledge on potential risks to human health from LEDs.

The Committee concluded that there is no evidence of direct adverse health effects from LEDs emission in normal use (lamps and displays) by the general healthy population. There is a low level of evidence that exposure to light in the late evening, including that from LED lighting and/or screens may have an impact on the circadian rhythm. At the moment, it is not yet clear if this disturbance of the circadian system leads to adverse health effects.

Vulnerable and susceptible population (young children, adolescent and elderly people) have been considered separately. Children have a higher sensitivity to blue light and although emissions may not be harmful, blue LEDs (between 400 nm and 500 nm) may be very dazzling and may induce photochemical retinopathy, which is a concern especially for children below three years of age. Elderly population may experience discomfort with exposure to LED systems, including blue LED displays (for example destination displays on the front of buses will be blurred).

Although there are cellular and animal studies showing adverse effects raising concerns particularly in susceptible population, their conclusions derive from results obtained using exposure conditions that are difficult to relate to human exposures or using exposure levels greater than those likely to be achieved with LED lighting systems in practice.

Reliable information on the dose-response relationship for adverse health effects for the case of the healthy general public is not available in the scientific literature for all wavelengths emitted by LED devices, although a threshold is identified for optical radiation in general based on experimental and injury data.

Since the use of LED technology is still evolving, the Committee considers that it is important to closely monitor the risk of adverse health effects from the long term LED usage by the general population.

Key words: Light Emitting Diodes (LEDs), risk assessment, health effects, SCHEER

Opinion to be cited as:

SCHEER (Scientific Committee on Health, Environmental and Emerging Risks), Preliminary Opinion on Potential risks to human health of Light Emitting Diodes (LEDs), 6 July 2017.

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http://ec.europa.eu/health/scientific_committees/experts/declarations/scheer_wg_en

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Two independent non-food Scientific Committees provide the Commission with the scientific advice it needs when preparing policy and proposals relating to consumer safety, public health and the environment. The Committees also draw the Commission's attention to the new or emerging problems that may pose an actual or potential threat.

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SCHEER

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1. SUMMARY

The purpose of the present SCHEER Opinion requested by the European Commission is to assess the potential health hazards associated with LED emissions in the general population due to LED usage.

The eye and skin are the most susceptible target organs for effects due to optical radiation, and action spectra also exist for effects on skin and eye (ICNIRP, 2013). The type of effect, injury thresholds and damage mechanisms vary significantly with wavelength. There are several variables to be taken into account when referring to effects of optical radiation from LEDs on human health: spectrum of a LED light source; intensity of the lighting, especially in the blue part of the spectrum; duration of exposure; exposure level at the eye or skin; health of the eye or skin; direct staring without deviation versus active eye movement.

The specific safety requirements and risk assessment methods regarding photobiological hazards are contained within several European safety standards. In order to assess the potential health hazards associated with LEDs, it is necessary to take into account all exposure parameters - the *irradiance* (the flux of optical radiation that reaches a target, distance dependent), the *radiance* (radiation flux leaving the source depending on emission angle, independent of distance to target), and the exposure duration.

People are exposed to optical radiation from a range of sources including different LEDs in any given 24-hour period. For many people, exposure to natural optical radiation will predominate, i.e. exposure to optical radiation from LEDs is likely to be insignificant compared with the exposure to natural light outdoors.

Potential health effects of LEDs in the general population

Published studies show that the blue light-weighted (for eyes) radiance from screens is less than 10% of the blue light photochemical retinal hazard limit, assuming viewing greater than about 3 hours (acute exposure), see Annex IV Dosimetry.

The search of the literature for the long-term impact of LED emissions on human health did not identify any studies since the technology has been recently distributed on the market for the general population. Because the technology is still evolving, it is important to continue monitoring the scientific literature.

The SCHEER concludes that the available scientific research does not provide evidence for health hazards to the eye or skin associated with LEDs when the total exposure is below the international agreed eposure limits (ICNIRP). However, issues in terms of flicker, dazzle, distraction and glare may occur.

It is expected that the risk of direct adverse effects will increase if these limits are exceeded. However, there is insufficient information in the scientific literature on the dose-response relationship for adverse health effects for optical radiation exposure of the healthy general public.

In addition, no evidence was found for increased risk of photosensitivity from LED lamps when compared with other lighting technologies. Indeed, the absence of ultraviolet radiation from general LED lamps may reduce the risk of photosensitivity for a number of these conditions.

Short-wavelength light (peak around 480 nm) influences the circadian system, but the full-action spectrum for the influence of light on the circadian system is not completely clear yet as other wavelengths have an influence as well. It has been shown that normal use of LEDs or screens illuminated by LEDs during the evening can perturb the circadian system, as do other types of artificial lights. LEDs with a higher component of short-wavelength light have increased impact on the circadian system, perhaps influencing sleep quality. At the moment, it is not yet clear if this disturbance of the circadian system leads to adverse health effects. Although there is some evidence that use of screens technology into the evening may impact sleep quality, it is not clear whether this is due to the optical radiation or the activity being carried out.

In addition, LEDs do have issues in terms of flicker, dazzle, distraction and glare.

Due to the point-source nature of some LED lighting, studies have shown that the light emitted leads to discomfort and glare.

Some lamps for illumination available on the market incorporate "point" LED sources without diffusers, which can cause glare if viewed. This was also reported to be a concern with some LED street lights.

Flicker from some LED lamps can result in stroboscopic effects. There are claims by small number people of adverse health effects such as migraine or headaches. There appear to be no technical reasons why LED lamps need to flicker since many models do not.

Potential health effects of particular LED sources (toys, car lights)

A European standard for electronic toys limits the emission of optical radiation from toys. Some LED emission spectra may induce photochemical retinopathy, which is a concern especially for children below about three years of age.

LEDs are used in virtual reality headsets where the screen is very close to eyes. However, the luminance of the source is very low and the exposure limits are not likely to be exceeded. The reported disorientation and nausea after extended use of these headsets is likely to be due to motion sickness rather than the optical radiation emitted by the screen.

The SCHEER is concerned about the high-luminance exterior sources used on some vehicles. Current examples appear to be blue-rich, which increases glare and scattering, particularly for older observers. The internal car lighting with LEDs that has replaced standard incandescent bulbs has emission levels that will result in exposures significantly below internationally agreed exposure limits. However, some exhibit pulsed emission modes that can result in phantom arrays when the head or eye is moved quickly. Such effects can be distracting. Distraction, dazzle and glare effects do not result in direct harm to the eye, but there could be consequences if the person exposed is carrying out a safety-critical task, such as driving.

Susceptible groups

As the eye ages scattering may increase. This is a particular problem for blue light. Therefore, older people may experience discomfort problems with exposure to LED systems, not clearly seeing the blue LED displays (such as destination displays on the front of buses).

People with degenerative and vascular disease of the retina may be more susceptible to harm from LEDs than the general population, but the risk is considered similar to that from other lighting sources with similar emission characteristics.

Although emissions from e.g. toys may not be harmful, blue LEDs may be very dazzling for young children.

Additional aspects to consider

The worst-case viewing condition is generally on axis viewing of an LED source, for example staring at a screen or an LED lamp. If a source is safe for viewing on axis it will be safe under all other viewing conditions at the same distance.

Flashing LED sources in the peripheral vision are more likely to cause distraction than those on axis.

LED lamps used for area illumination are usually more energy efficient than other sources, e.g. incandescent lamps. For the same colour temperature, the blue light component of the optical emission is similar to an incandescent lamp. However, the infrared (and possible ultraviolet emission) will be greatly reduced or absent, which might influence the normal bioprocesses in humans. This aspect is still under investigation.

2. MANDATE FROM THE EU COMMISSION SERVICES

2.1 Background

The Light-Emitting Diode (LED) is a semiconductor light source that releases energy in the form of light when a suitable voltage is applied to it. LEDs are used in home lighting, laptop and phone screens, TV sets, traffic signals and increasingly becoming used as a light source in the automotive industry to mention a few applications.

The LEDs are energy efficient and last much longer than the conventional light sources, which make them widely used by the general population. Hence it is important to know the implications of LED radiation on the human health.

Recently, researchers have analysed potential risks of white LEDs [1], issuing recommendations to avoid the hazards. Another group of researcher has speculated about the effects of LED radiation on retinal epithelium cells (RPE) [2],

The human visual system is exposed to high levels of natural and artificial lights of different spectra and intensities along lifetime. These lights give rise to the formation of reactive oxygen species and induce mutagenic mechanisms which lead to apoptosis and consequently to degenerative eye diseases, such as age-related macular degeneration (AMD).

There are several variables to be taken into account when referring to LEDs effects on human health: 1) spectrum of a LED light source, 2) intensity of the lighting, especially in the blue band, 3) duration of exposure, 4) health of the eye, 5) direct staring without deviation versus active eye movement.

According to the SCENIHR Opinion on the artificial light[1]: "blue radiation directly from bright cold white light sources in proximity of the workers eyes (e.g. task lights) or strong projectors (floodlights, accentuation and scenic lighting, etc.), or reflected may represent a risk for retinal damage; the blue light component from cold white reading lights may perturb circadian rhythm of the user; a child's crystalline lens is more transparent to short wavelengths than that of an adult, making children more sensitive to blue light effects on the retina."

Legal background

At international level, recommendations for exposure limit values (ELVs) to protect against adverse effects of optical radiation are established by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and apply both to the occupational population and the general public.

At EU level, the following legal framework exists that aims at minimising the risks posed by the LEDs.

Regarding the protection of the occupational population, the ELVs of Directive 2006/25/EC[2], which set the minimum safety requirements regarding the exposure of workers to risks arising

[1] http://ec.europa.eu/health/scientific_committees/emerging/docs/scenihr_o_035.pdf

[2] Directive 2006/25/EC of the European Parliament and of the Council of 5 April 2006 on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC), JO L 114 of 27.04.2006

from artificial optical radiation, are based on the ICNIRP recommendations applicable at the time of publication[3].

Furthermore, the safety of LEDs (unless they are less than 50 V AC or 75 V DC) falls under the scope of the Low Voltage Directive (LVD) 2014/35/EU[4]. LEDs must comply with the safety objectives of Annex I of the Directive that include all type of risks, guaranteeing a high level of protection of health and safety of persons.

If LEDs are less than 50 V AC or 75 V DC, their safety is covered by the General Product Safety Directive 2001/95/EC[5].

All European standards (EN) related to LVD are voluntary, but if harmonised and published in the Official Journal of the European Union, they would provide presumption of conformity with the safety objectives of the LVD.

EN 62471 on the "Photobiological safety of lamps and lamp systems" sets a risk group structure and methods to assess the photo-biological risks of lamps including LEDs.

The specific safety requirements regarding photobiological hazards are contained within the LED modules and luminaire safety standards (EN 62031 and EN 60598-series) and in other lamp safety standards: EN 62560 and EN 62776.

2.2 Terms of Reference (ToR)

The Scientific Committee is asked to assess the safety risks associated with the use of LEDs and to provide an answer to the following questions:

1. What are the potential health hazards associated with LEDs emission in the general population with regard to wavelength, intensity, duration and viewing position?

2. If possible, identify dose response relationship associated with LEDs emission in the general population with regard to wavelength, intensity, duration and viewing position?

3. What are the potential health risks associated with LED displays (e.g., TV sets, laptops, phones, toys and car lighting) in the general population and in vulnerable and susceptible populations (e.g., children and elderly people)?

4. What are the potential health risks associated with LED lamps (e.g., toys and car lighting) in the general population and in vulnerable and susceptible populations (e.g., children and elderly people)?

[3] International Commission on Non-Ionizing Radiation Protection (ICNIRP): "Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38 to 3 μm)", Health Physics 73 (3), 539-554 (1997) http://www.icnirp.org/cms/upload/publications/ICNIRPbroadband.pdf
International Commission on Non-Ionizing Radiation Protection (ICNIRP): "Guidelines on limits of exposure to ultraviolet radiation of wavelengths be-tween 180 nm and 400 nm (incoherent optical radiation)", Health Physics 87 (2), 171-186 (2004)
http://www.icnirp.org/cms/upload/publications/ICNIRPUV2004.pdf

[4] Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits, OJ L 96, 29.3.2014, p. 357–374

[5] Directive 2001/95/EC of the European Parliament and of the Council of 3 December 2001 on general product safety, OJ L 11, 15.1.2002, p. 4–17

3. OPINION

The SCHEER replies to the questions in the terms of reference.

Q1. What are the potential health hazards associated with LEDs emission in the general population with regard to wavelength, intensity, duration and viewing position?

LEDs are optical radiation emitters. Optical radiation does not penetrate the body; the eye and skin are the organs that are most susceptible to damage.

The risks following exposure to optical radiation hazards are a complex function of wavelength and exposure conditions. International organizations, such as the International Commission on Non-Ionizing Radiation Protection (ICNIRP), have produced weighting functions for different hazards associated with optical radiation. ICNIRP guidelines for optical radiation in general do not differentiate between exposure to professionals and exposure to the general public.

The type of effect, injury thresholds, and damage mechanisms vary significantly with wavelength. The effects may overlap and have to be evaluated independently. Action spectra at selected wavelengths, intensity, duration, exist for specific chemical reactions in skin and eye.

The SCHEER takes these action spectra for the following parameters: wavelength, intensity, duration and viewing position to assess the potential hazard.

Wavelength

Most current white-light LED lighting devices (blue LED and yellow phosphor) emit blue light combined with green/yellow light without significant red or any near infrared wavelengths. It is under investigation whether the absence of near infrared wavelengths has any health implications. Many people perceive white colour 4000 K LED lighting as harsh because almost thirty percent of the spectrum is emitted as blue light, but direct adverse health effects are unlikely.

The blue light photochemical retinal hazard to the eye from domestic LED lighting is between 10-20% of the relevant ICNIRP exposure limit, assuming viewing longer than about 3 hours. For a comparison, 14% of that limit corresponds to a mid-range incandescent lamp. The ICNIRP guidelines are based on observed eye or skin injury after experimental exposure of animals and on information from human accidents. Reduction factors are used in setting the exposure limits for humans when animal studies are used.

Intensity

Radiant intensity (W/sr) is a parameter characterising the emission of the source, while luminous intensity (lm/sr) is important in terms of visual perception including distraction, glare and after-images.

The optical radiation incident on a target tissue is expressed in terms of irradiance (W/m²) or illuminance (lm/m² or lux).

For photochemical processes, the effect is a function of not only the irradiance (or radiance) but also of the exposure duration. The product of these two factors gives the dose (the radiant exposure (J/m²) or radiance dose (J/m²sr)). The irradiance (or radiance) used in this calculation of effects is weighted by the appropriate action spectrum. A person will receive exposure to optical radiation from a range of sources including different LEDs in any given 24-hour period. In order to assess the potential health hazards associated with LEDs, it is necessary to take into account all of these exposures. For many people exposure to natural optical radiation will predominate, i.e. exposure to optical radiation from LEDs is likely to be insignificant compared with the exposure to natural light outdoors. The SCHEER concludes that

the available scientific research does not provide evidence for health hazards associated with LEDs when the total exposure is below the ICNIRP exposure limits. However, issues in terms of flicker, dazzle, distraction and glare may occur.

Animal experiments and in vitro studies suggest that cumulative blue light exposure below the levels causing acute effects also can induce photochemical retinal damage. The search of the literature for long-term impact of LED emission on human health did not identify studies investigating the healthy general population. However, technology is still evolving and it is important to continue to monitor the literature.

Due to the point-source nature of some LED lighting, studies have shown that these emitters can cause discomfort and glare.

It has been shown that normal use of LEDs or screens illuminated by LEDs during the evening can perturb the circadian system influencing sleep quality, because of the high component of the short-wavelength light (peak around 480 nm). However, the full action spectrum for the influence of light on the circadian system is not completely clear yet, as other wavelengths have an influence as well. At the moment, it is not yet clear if this disturbance of the circadian system leads to adverse health effects. Although there is some evidence that use of screens technology into the evening may impact sleep quality, it is not clear whether this is due to the optical radiation or the activity being carried out.

Viewing position

The worst-case viewing condition is generally on axis viewing of a LED source, for example staring at a screen or a LED lamp. If a source is safe for viewing on axis it will be safe in all other viewing conditions at the same distance. However, flashing LED sources in the peripheral vision are more likely to cause distraction than those on axis.

Q2. If possible, identify dose response relationship associated with LEDs emission in the general population with regard to wavelength, intensity, duration and viewing position

Reliable information on the dose-response relationship for adverse health effects for the case of the healthy general public is not available in the scientific literature for all wavelengths emitted by LED devices, although a general threshold is identified for optical radiation in general based on experimental and injury data.

If the exposure is below ICNIRP exposure limits, the SCHEER is not aware of any risk of damage to the eye and skin. The risk of damage to the eye or skin will increase if ICNIRP exposure limits are exceeded. However, the profile of the dose-response relationship is not well known.

Since LED emission characteristics like exposure patterns and spectra (wavelength-dependent intensity) vary from one emitter to another, it is not possible to predict the profile of the dose-response function for a general LED emitter.

Q3. What are the potential health risks associated with LED displays (e.g., TV sets, laptops, phones, toys and car lighting) in the general population and in vulnerable and susceptible populations (e.g., children and elderly people)?

Evaluating the retinal blue light hazard effectively requires taking account of the irradiance of the retinal image of the source viewed. For momentary viewing, the retinal image subtends the same angle as does the source. With increasing exposure time, the retinal image is spread over an increasingly large area of the retina due to eye movement (saccades) and task-determined movement, resulting in a corresponding reduction in retinal irradiance. A time-dependent function of the angular subtense of the retinal image for exposures from 0.25 sec (aversion response time) to 10,000 sec is defined, ranging from 1.7 mrad (taken as the smallest image formed on the retina) to 100 mrad.

Published studies show that the blue light weighted radiance from screens is less than 10% of the blue light hazard limit that is defined to protect the retina regarding photochemically induced injury.

Light from screens, independent of the wavelength, has been shown to influence the circadian system. There is some evidence that use of screen technology into the evening may impact sleep quality. However, it is not clear whether this is due to the optical radiation or the activity being carried out.

There is an European standard for electronic toys that limits the emission of optical radiation from toys. However, children have a higher sensitivity to blue light and although emissions may not be harmful, blue LEDs may be very dazzling for young children. Some LED emission spectra may induce photochemical retinopathy, which is a concern especially for children below about three years of age.

Internal car lighting with LEDs has replaced standard incandescent bulbs. However, emission levels are significantly below ICNIRP exposure limits for blue light to eyes. Since many such LED sources are operated in pulsed emission modes this can result in phantom arrays when the head or eye is moved quickly. Such effects can be distracting.

As the eye ages scattering may increase. This is a particular problem for blue light. Therefore, older people may experience discomfort with exposure to LED systems, including blue LED displays (for example destination displays on the front of buses will be blurred).

People with degenerative and vascular disease of the retina may be more susceptible to harm from LEDs than the general population, but the risk is considered similar to that from other lighting sources with similar spectral characteristics.

LEDs are used in virtual reality headsets where the screen is very close to eyes. However, the luminance of the source is very low and the exposure limits are not likely to be exceeded. Manufacturers give guidance on maximum duration of use for such headsets. Some people report disorientation and nausea after extended use of these headsets. This is likely to be due to the motion sickness rather than the optical radiation emitted by the screen.

Q4. What are the potential health risks associated with LED lamps (e.g., toys and car lighting) in the general population and in vulnerable and susceptible populations (e.g., children and elderly people)?

LED lamps used for area illumination are usually more energy efficient than other sources and therefore consumers have been encouraged to use them instead of, for example, incandescent lamps. Most domestic applications are likely to use retrofit lamps. For the same colour temperature, the blue light component of the optical emission is similar to an incandescent lamp. However, the infrared emission will be greatly reduced or absent, which might influence the normal bioprocesses in humans and is still under investigation.

It is good practice in lighting design to ensure that lamps for illumination are either positioned outside of the usual field of view or are of such low luminance that the source does not produce significant glare. Some sources available on the market incorporate "point" LED sources without diffusers, which can cause glare if viewed. This was also reported to be a concern with some LED street lights.

Flicker has been measured at 100 Hz from some LED lamps. It is not possible for consumers to identify which LED lamps flicker and which do not at the point of purchase. Since some LED lamps flicker with almost 100% modulation, this can result in stroboscopic effects (for example a waved hand appears as a series of stationary images). There are claims by a small number of people for adverse health effects such as migraine or headaches. Although not a direct adverse health effect, it is foreseeable that any moving machinery (including food mixers) may appear stationary at particular speeds under flickering LED lamps. There appear to be no technical reasons why LED lamps need to flicker since many models do not. However, the use of a dimmer switch may introduce flicker in LED lamps that do not flicker on full power.

The SCHEER is concerned about the high luminance sources used on some vehicles, particularly daylight running LED lights that remain on without dimming at night. Current examples appear to be blue-rich, which increases glare and scattering, particularly for older observers. There are claims that these running lights are a greater glare source in fog than more traditional vehicle lighting. However, the SCHEER is not aware of any risk of direct harm to the eyes from the blue light component of external vehicle LED lighting at normal viewing distances, although if a driver's vision is impaired this could result in accidents.

Apart from the concern over flicker, no evidence was found for increased photosensitivity risk from LED lamps when compared with other lighting technologies. Indeed, the absence of ultraviolet radiation from general LED lamps may reduce the risk of photosensitivity for a number of these conditions.

There is a European standard for electronic toys that limits the emission of optical radiation from toys. However, children have a higher sensitivity to blue light and although emissions may not be directly harmful, blue LEDs may be very dazzling for young children.

Additional information

Many LEDs contain toxic substances and in order to assess their potential health impact/effect there is a need for further research on waste management. In normal use, there is no evidence of harm from these toxic substances since substances do not leach from LED modules.

4. MINORITY OPINIONS

No minority Opinion.

5. DATA AND METHODOLOGY

The general approach by the Scientific Committee to health risk assessment is to evaluate all available evidence from human and mechanistic studies regarding effects to exposure to the agent of concern and then to weigh this evidence together across the relevant areas to generate a combined assessment.

Throughout the Opinion, consistency and adherence to the International System of Units (SI) regarding the use of terms and units has been used. For definitions and abbreviations please refer to the Glossary of terms and to Abbreviations.

5.1 Data/Evidence

Data

The primary source of scientific data for this Opinion was papers and reports published in international peer reviewed scientific journals in the English language available on PubMed, Scopus and Web of Science. Information has also been taken from technical reports from different agencies and bodies. The literature review carried out is outlined in Annex VII, including the search key words used.

The overall quality of the studies is taken into account in a tiered approach (Figure 1), as well as the relevance of the studies for the issue in question.

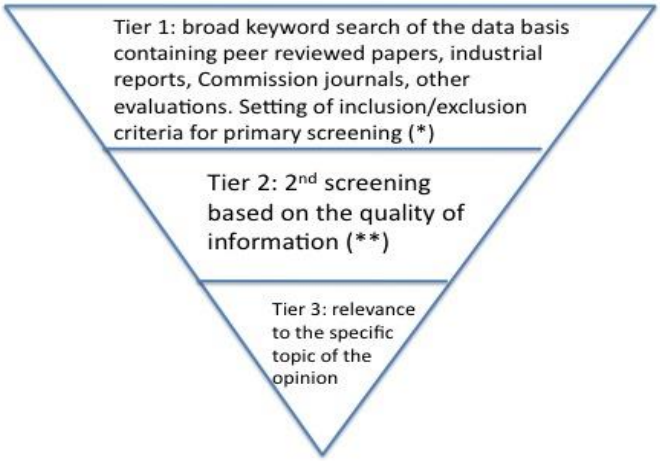

Fig. 1: Tiered approach in selection of publications based on their relevance and quality

Evidence

The health risk assessment evaluates the evidence within each of the identified areas and then weighs the evidence together across the areas to generate a combined assessment. This combined assessment addresses the question of whether or not a hazard exists, i.e. if there is a causal relationship between exposure and some adverse health effect.

In the present Opinion, the potential risks to human health of LEDs have been assessed by reviewing the literature on epidemiological studies, experimental studies in humans,

experimental studies in animals and mechanistic in vitro studies.

5.2 Methodology

The potential health risks to human health of LEDs have been studied via different approaches as controlled studies, case reports, and experimental studies in animals. Also keeping the benefits from the LED lighting in mind, the risk from the LED optical radiation hazard may be managed by exposure optimisation. This is shown in figure 2, below.

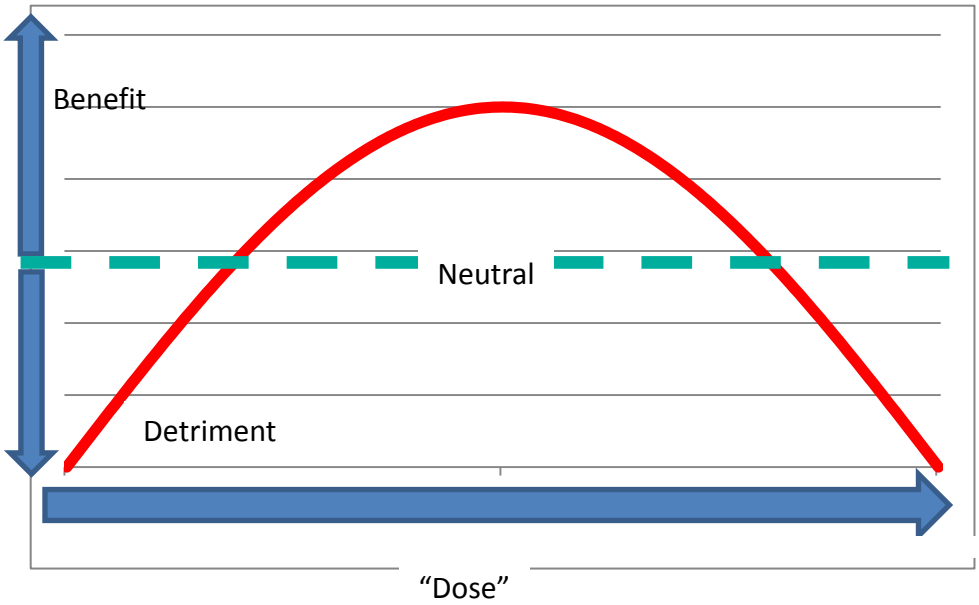

Fig. 2: Plot of benefit vs detriment showing that detriment may increase as dose reaches low levels.

The shape of the curve in figure 2 depends on a number of factors, such as the part of the optical spectrum under consideration, time of exposure, prior exposure, possibly age and individual differences (such as photosensitivity, eye pathologies, etc.).

The risk assessment approach used in this Opinion is based on that promoted by the European Commission for workplaces (EC 1996) and for products used by consumers (EC 2015).

This Opinion is primarily concerned with the risk arising following exposure of the eyes or skin to optical radiation from LEDs. Therefore, this will be considered the hazard. It may be necessary to quantify the hazard using an appropriate metric, but usually quantification is only relevant if the optical radiation geometry and distance substantiate the risk of exposure of people. If exposure is possible then the exposure scenario needs to be considered. For example, if the source of exposure is an indicator LED, or if it forms part of a display screen, then it is very likely that people will view the source. However, for many illumination sources, the LED should be shielded from direct viewing and such direct viewing will be likely only under accidental or improper use conditions. Once an exposure scenario has been identified, the optical radiation exposure conditions, for example of the eye or skin, will need to be quantified and compared with relevant limits. These limits may be instantaneous limits or time-averaged limits. In the latter case, exposure from a number of different sources throughout a day will need to be considered. If the exposure is less than the relevant limit, then the risk of adverse health effects is considered low. This assessment needs to be carried out under normal use of the LED and under reasonably foreseeable conditions of misuse.

In addition to consideration of direct harm, the risk assessment also needed to consider issues that may arise from direct viewing of some LED sources where the risk arises due to the

adverse impact of the optical radiation on vision, such as distraction, glare and after-images. These effects depend not only on the optical radiation incident on the eye, but also the ambient light level and the task being carried out at the time of exposure.

A third category of risk is potentially due to the temporal characteristics of the optical radiation emitted by the LED. The potential effects may be due to the actual emission of the source as directly viewed, or due to head or eye movement, or to the impact on moving equipment.

A fourth category is where exposure to optical radiation from an LED may impact on circadian rhythm or other aspects of wellbeing.

These issues are addressed in this Opinion.

6. ASSESSMENT

6.1. Photometry and radiometry

LED characteristics including physical size, flux levels, spectrum and spatial distribution, separate them from typical element sources, which are generally employed and measured for photometric and radiometric quantities. For every radiometric quantity there is a photometric analogue.

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye. It is distinct from radiometry, which is the science of measurement of radiant energy (including light) in terms of absolute power. Concepts such as radiance, irradiance, radiant power and radiant intensity used in radiometry can easily be defined via simple geometric relationships. While sharing these identical relationships, photometry also introduces detector response modelled after human visual characteristics.

Radiometry deals with the measurement of electromagnetic radiation across the total spectrum (infrared, visible, ultraviolet and beyond). Photometry is concerned only with the visible portion of the spectrum, from about 380 nm to 780 nm and measures luminous flux, luminous intensity, illuminance, and luminance.

All radiometric and photometric quantities are defined in detail in the glossary.

Table 1 indicates the symbols and the units of the quantities; the indices "e" = "energetic"; "v" = "visual".

Table 1: Radiometric and photometric quantities

Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumen (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m^2	Illuminance	E_v	lm/m^2 or lux
Radiance	L_e	W/m^2 sr	Luminance	L_v	lm/m^2 sr

The luminosity function or luminous efficiency function describes the average spectral sensitivity of human visual perception of brightness. It is based on subjective judgements of which of a pair of different-coloured lights is brighter, to describe relative sensitivity to light of different wavelengths. As defined by the Commission Internationale de l'Éclairage (CIE) the luminosity function V(λ) is a standard function, which may be used to convert radiant energy into luminous (i.e., visible) energy (see Annex IV Photometry and Radiometry for details).

6.2 Physical characteristics of LEDs sources

The basic technology of an LED is that of a conventional diode, i.e., the creation of a positive-negative or p-n junction by doping (impregnating) semiconductor materials with impurities. In a p-n junction, current can flow from the p-side of the material to the n-side, but not in reverse. As electrons move and meet holes, they fall into a lower energy level by the emission of photons. The wavelength (colour) of the light thus emitted depends on the band gap energy of the semiconductors that form the p-n junction. It should be noted, however, that there are situations (e.g., silicon or germanium diodes) where the recombination of electrons and holes does not lead to an optical emission.

The spectral irradiance for a domestic retrofit LED lamp is shown in the figure 3, with the spectrum from an incandescent lamp for comparison. However, the emission spectrum depends on the type of LED. In particular, for white light LED lamps, the emission may be produced by a blue LED accompanied by a broad emission phosphor (as shown in the figure 3) or by multiple LEDs emitting different colours that can be mixed in various proportions to produce ”white” of different colour temperatures.

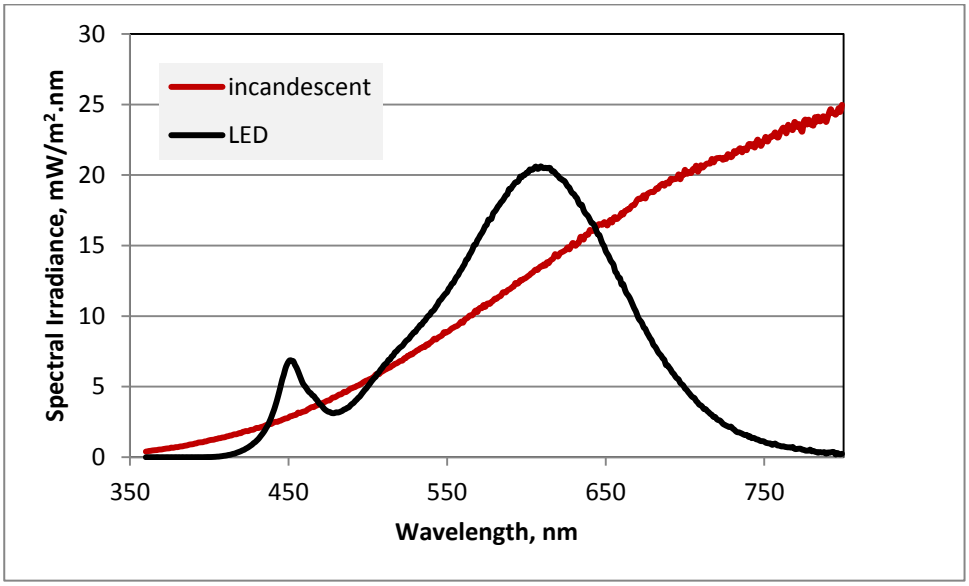

Fig. 3: Emission spectra for an incandescent lamp and an equivalent LED lamp

It is important to put exposure to optical radiation from LEDs into context with natural optical radiation sources. The data above is shown in the figure 4 on a log/linear scale for the spectral irradiance for comparison with a blue sky (minus any direct contribution from the sun). It can be seen that the spectral irradiance from the sky is about two orders of magnitude greater than from the LED or incandescent lamp over a considerable part of the spectrum shown.

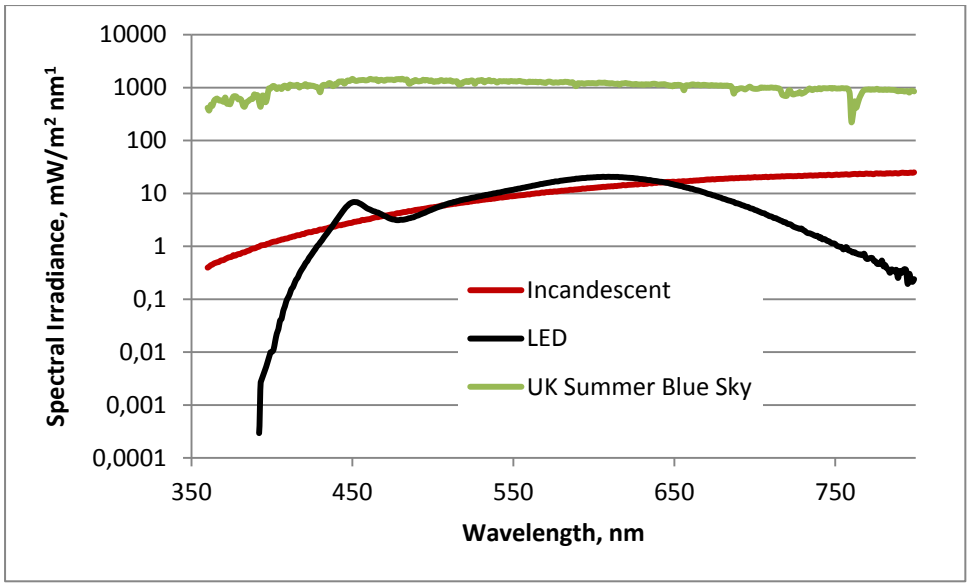

Fig. 4: Comparison of the spectral irradiance from a blue sky with the LED and incandescent lamp shown in the figure 3.

Infrared LEDs (IRLEDs) have been used for many years in, for example, remote control systems. Although LED technology is still developing, ultraviolet (UV) LEDs have not yet replaced traditional sources of UV radiation in many applications.

Further information on LED technology is contained in Annex I.

6.3 Point source vs diffuse source

In this report it is necessary to differentiate not only between point source light (light emitted from a LED chip) and diffused light LED sources, but also between diffused light that illuminates the environment and diffused light emitted by (for example) a LED screen that is directly viewed by users. In this sense, the exposure conditions (irradiance, distance from source and exposure duration) are totally variable and should be considered independently. For example, screens are mostly tactile and the distances of use are dependent on the length of the arms of the user and the quality of their eyesight. However, at any given time, a person is likely to be exposed to optical radiation from a range of different optical radiation sources, including optical radiation from the sun. Any exposure to optical radiation from LEDs needs to put into context.

To save energy, the European directives from the Eco-design of Energy Using Products (2005/32/CE) have recommended the replacement of incandescent lamps by more economic devices such as LEDs. However, the emission spectra from earlier types of white-light LEDs were rich in blue radiation, known to be potentially dangerous to the retina for high radiant exposures (Krigel *et al.*, 2016). Therefore, it is important to consider actual source characteristics and exposure conditions.

There are several variables to be taken into account when referring to effects of optical radiation from LEDs on human health: 1) spectrum of a LED light source, 2) intensity of the lighting, especially in the blue part of the spectrum, 3) duration of exposure, 4) exposure level at the eye or skin, 5) health of the eye or skin, 6) direct staring without deviation versus active eye movement.

6.4. The fundamental interaction between light and matter

Light (or more generally optical radiation) reacts with matter in various ways. These interactions are based on the absorption of the optical radiation by matter. When the energy of a photon is taken up by matter, reflection (the electromagnetic radiation is returned either at the boundary between two media or at the interior of a medium), refraction (change in direction of wave propagation due to a change in its transmission medium), scattering (the process of deflecting a unidirectional beam into one or many directions), or transmission (the passage of electromagnetic radiation through a medium) (Das, 1991; Elliott, 1995; Hillenkamp, 1989).

There are four basic interactions that can occur following absorption of optical radiation: photothermal, photochemical, photomechanical and photoelectric interactions (see Annex II for details). However, only the first two are relevant to the optical radiation from current LEDs.

6.5. Eye optics fundamentals

A diagram of the human eye, showing the significant anatomical details, is shown below.

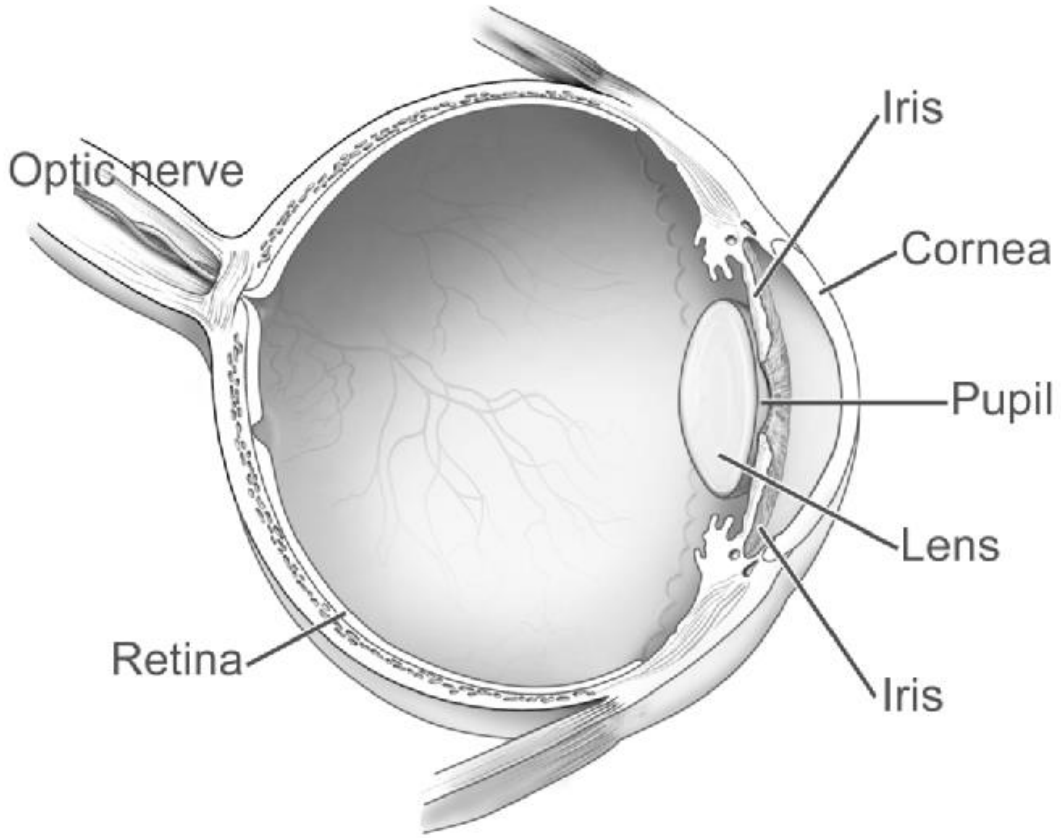

Fig. 5: A diagram of the human eye (source: © National Eye Institute, National Institutes of Health)

The visual sensitivity of the eye to optical radiation varies with wavelength between about 380 and 780 nm. The wavelength range varies between individuals and the absolute response also has a distribution. However, the International Commission on Illumination (CIE from the

French, Commission Internationale de l'Eclairage) have published response curves for so-called standard observers, based on experimental studies, taking account of whether the light levels are high (day time), low (night time) or in between. These are termed photopic, scotopic and mesopic curves, respectively. The photopic and scotopic curves are shown in figure 6.

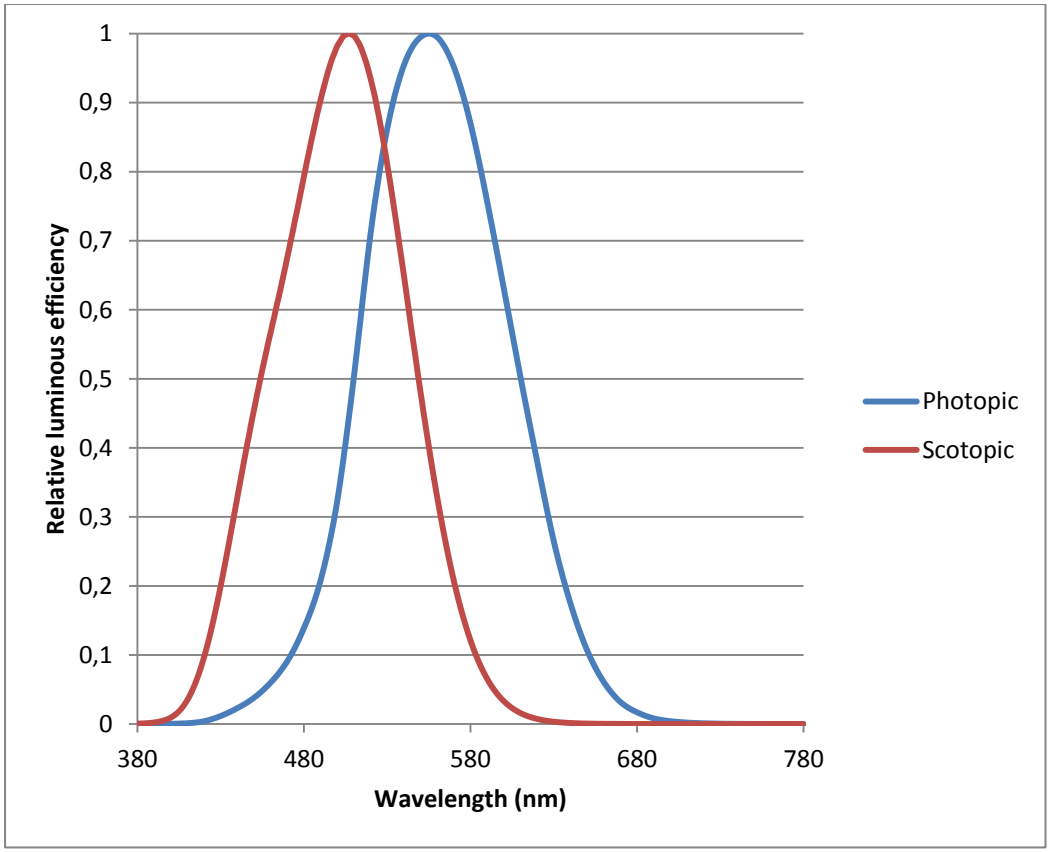

Fig. 6: Relative luminous efficiency for photopic and scotopic vision

6.5.1 Thermal and photochemical aspects

The risk of thermal effects is related to burns to the retina, generally resulting from short-term exposure to very intense visible and IR-A radiation. Lesions occur on the outer retina (photoreceptors and cells of the pigment epithelium) and appear after some time has passed (usually about 24 hours). With photochemical interactions, first, reactive oxygen species may be generated, second, the presence and action of these represent oxidative stress, and unless repair mechanisms and detoxification processes alleviate the impact, cell death (any type) may occur. Photoreactive pigments (lipofuscin) in the epithelium accumulate with age, increasing the risk of oxidative stress. The photopigment fragments thus created act as free radicals, which may lead to the death of the photoreceptor cells (Kuse *et al,* 2014; Chamorro *et al.*, 2013). The radiation absorbed, which depends on the radiance of the light source and the duration of exposure, causes photochemical decomposition of the pigments present in the photoreceptor cells.

The retina is exposed to all of the visible wavelength range, the most severe retinal damage is likely to result from the effects of the shorter wavelengths (400-600 nm); this is commonly known as the "blue-light-hazard" (see action spectrum below, ICNIRP 2013). However, the retina contains a number of endogenous photosensitisers (such as vitamin A derivatives, lipofuscin, melanin, flavins, porphyrins and rhodopsin) which can be excited by visible/infrared radiation reaching the retina (Rozanowska *et al.,* 1995*)*. The retina contains many chromophores that can lead to photochemical damage when excited at each wavelength of light. Optical radiation emitted by LEDs may induce cell damage depending on the wavelength and therefore some wavelengths may produce more severe retinal photoreceptor cell damage

than other wavelengths. (Chamorro, *et al.,* 2013*).* Short wavelength light can penetrate through tissues to the cells and their organelles, inducing the generation of reactive oxygen species (ROS) in RPE mitochondria and even apoptosis (Roehlecke, *et al.,* 2009*)*. Also, optical radiation emitted by LEDs can cause a phototoxic effect, especially from the most energetic radiations: the violet and blue (400 – 500 nm) (Godley *et al.*, 2005). The higher toxicity of the blue part of the spectrum is recognised in the ICNIRP action spectrum for the blue light hazard shown in figure 7. Also shown in figure 7 is the aphakic action spectrum, intended for people without a lens, but which can also be applied for very young children.

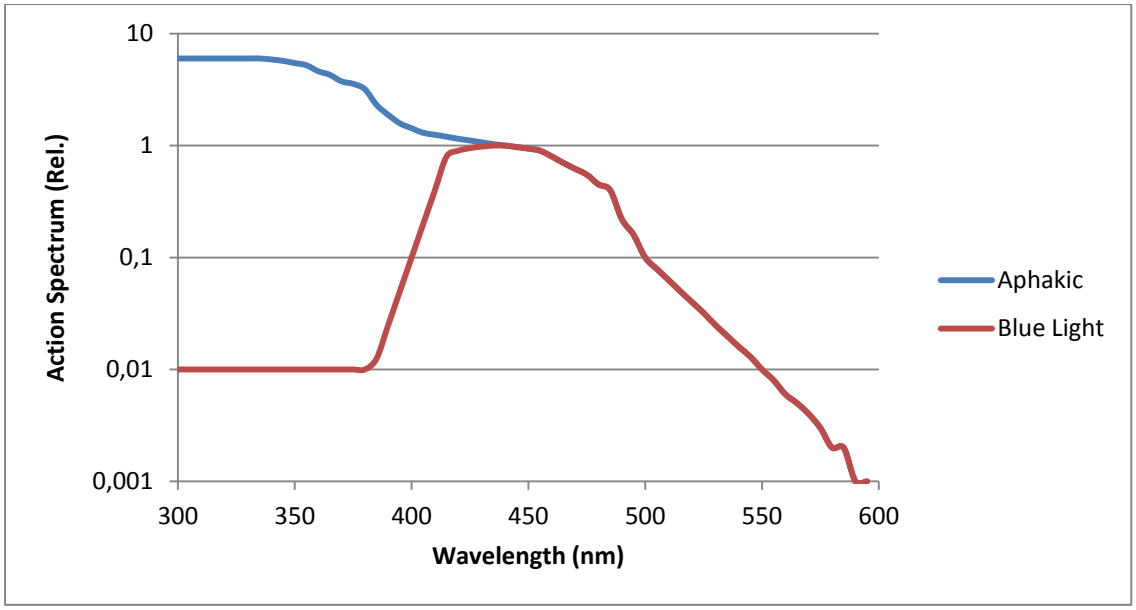

Fig. 7: ICNIRP Blue Light and Aphakic Eye Action Spectra

6.5.2. The effects on the healthy eyes

6.5.2.1. Computer Vision Syndrome

Computer vision syndrome (CVS) is the combination of eye and vision problems associated with the use of computers and was a concern before the introduction of LED screens. In modern society the use of computers for both vocational and avocational activities is almost universal. However, CVS may have a significant impact not only on visual comfort but also occupational productivity since between 64% and 90% of computer users experience visual symptoms which may include eyestrain, headaches, ocular discomfort, dry eye, diplopia and blurred vision either at near or far distance after prolonged computer use. Rosenfield (2011) reviewed the principal ocular causes for this condition, namely oculomotor anomalies and dry eye. Accommodation and vergence responses to electronic screens appear to be similar to those found when viewing printed materials, whereas the prevalence of dry eye symptoms is greater during computer operation. The latter is probably due to a decrease in blink rate and blink amplitude, as well as increased corneal exposure resulting from the monitor frequently being positioned in primary gaze.

The aim of another study (Argiles *et al.*, 2015) was to evaluate spontaneous eye blink rate (SEBR) and percentage of incomplete blinks in different hard-copy and visual display terminal (VDT) reading conditions, compared with baseline conditions. Its conclusions are that the high cognitive demands associated with a reading task led to a reduction in SEBR, irrespective of type of reading platform. However, only electronic reading resulted in an increase in the percentage of incomplete blinks, which may account for the symptoms experienced by VDT users.

6.5.2.2 Anterior Segment of the Eye

To date there is no evidence that commercially available LED light sources have a deleterious effect on the anterior segment (conjunctiva, cornea and lens) of the human eye.

It has been reported that the severity of damage induced by light depends on radiation intensity, radiation wavelength and time of exposure (Lee *et al.*, 2016). To date there are scientific reports showing that blue LED light at high doses (i.e. in excess of exposure limits) is toxic for the ocular surface. The excess of blue light LED radiation stimulates the production of pro-inflammatory cytokines (e.g., IL-1, IL-6, and IL-8, through the c-jun amino-terminal kinase [JNK] pathway, p38 pathway, and nuclear factor– kB [NF-kB] pathway) and enzymes (e.g. MMP-1) that mediate prostaglandin and leukotriene biosynthesis, as well as antioxidant enzymes in corneal epithelial cells (Lee *et al.*, 2016).

The overexposure to emitting blue radiation (410 nm) at 50 J/cm^2 can induce oxidative damage and apoptosis to the cornea, which may manifest as increased ocular surface inflammation and resultant dry eye compared to LED light emitting red and green irradiation (Lee *et al.*, 2016).

Regarding the lens, cataract is the major cause for legal blindness in the world (Ide *et al.*, 2015). Oxidative stress on the lens epithelial cells is the most important factor in cataract formation. Cumulative light-exposure from widely used LEDs may pose a potential oxidative threat to the lens epithelium. However, blue light exposure from the sky dominates and exposure to blue light from current LEDs is a small additional contribution to the natural exposure.

Previous authors (Xie *et al.*, 2014) analysed the photobiological effect on human lens epithelial cells (hLECs) of white LED light exposure with multichromatic correlated colour temperatures (CCTs) of 2954, 5624, and 7378 K. In vitro experiments showed that compared with 2954 and 5624 K LED light, LED light having a CCT of 7378 K caused overproduction of intracellular reactive oxygen species (ROS) and severe DNA damage, which triggered cell cycle arrest and apoptosis. These results indicate that white LEDs with a high CCT could cause significant photobiological damage to hLECs.

Caution should be exercised regarding the effect of LED light on human lens as this study was conducted using human lens epithelial cells in cultures. Responses against blue light irradiation might be variable in clinical situations involving human subjects. Humans are not ordinarily exposed to blue light with high radiant exposure, as they were in experimental studies. It is possible that under specific occupational circumstances, humans may be exposed to high radiant exposure blue light. However, existing European legislation for the exposure of workers to artificial optical radiation would apply.

Some concern should be raised for medical professionals working under intensive shadowless lamps in the operating room. The incandescent or halogen light sources for surgical lamps are being replaced by more energy-efficient light emitting diodes (LEDs). However, occupational exposure legislation will apply.

6.5.2.3 Posterior Segment of the Eye

The present review did not identify any peer-reviewed literature demonstrating damage of the posterior segment of the human eye following exposure to optical radiation from commercially available white LED lamps in everyday life. Data are available only concerning the effect of LED light exposure or overexposure for in vitro or in vivo animal model studies.
Some concerns regarding possible hazard of LED light exposure comes from the fact that white light from LEDs appears normal to human vision, however a strong peak of blue light ranging from 460 to 500 nm is also emitted within the white light spectrum; this blue light corresponds to a potential retinal hazard, but only at levels significantly in excess of the exposure limits recommended by ICNIRP (Behar-Cohen *et al.*, 2011). See also figure 3 for a comparison with the exposure to optical radiation from a blue sky.

The composition of the white-light spectrum differs among LED products and their light qualities may change over time. Although it is robust in the beginning, a white light LED may

progressively release more short-wavelengths (blue light) when LED lumen depreciation occurs because of phosphor degradation. The quality of the light deteriorates after the lights pass below the 70% lumen maintenance level (U.S. Department of Energy 2009). These characteristics suggest that a white LED might cause more blue light exposure than other domestic lighting sources at the end of their life. Cumulative exposure to blue light has been argued to accelerate aging of the retina and possibly play an etiological role in age-related macular degeneration (Behar-Cohen *et al.*, 2011).

Irradiating human RPE cells in vitro with three different LED light sources - blue (468 nm), green light (525 nm), red-light (616 nm) or white light at an irradiance of 5 mW/cm^2 induce a significant reduction of the viability of the cells for all four LEDs light (Chamorro *et al.*, 2013). However, ROS levels increased only after the exposure with blue, green or red light but not after the exposure to white light compared to non-irradiated cells, although there was an increased degradation of nucleic acids in all irradiated cells in comparison with control cells. Notwithstanding, apoptosis cell death also increases significantly following white light exposure (blue 86%, green 84%, red 66%, white 89%) compared to only 3,7% of apoptosis of the non-irradiated RPE cells. Summing up, three light–darkness cycles (12 h/12 h) exposure to LED lighting, including white LED, affect the growth of RPE cells and produce cellular stress, increasing ROS levels as well as increasing DNA damage and the number of apoptotic cells.

LED light at domestic lighting levels induced retinal injury in a Sprague-Dawley (albino) rat model after chronic exposure (Shang *et al.*, 2014; Shang *et al*., 2017). Retinal cell function loss was demonstrated *in vivo* by electrofunctional test showing a significant decrease of b-wave amplitude after 9 and 28 days of blue or white LED, or compact fluorescent lamp (CFL), light exposure. The findings were confirmed *ex vivo* by a significant thinning of the outer nuclear layer where the nuclei of photoreceptor cells are located and more apoptosis after blue and white LED light exposure, compared with the exposure to the light from the CFL. The retina has one of the highest oxygen consumption levels of tissues in the body and it is sensitive to oxidative stress (Yu and Cringle, 2005). Oxidative stress is the crucial risk factor for photoreceptor degeneration, which is caused by the generation of toxic ROS within retinal tissue. The retina contains enzymes involved in detoxification or synthesis, particularly in the outer segment or retinal pigment epithelium (Shang *et al.*, 2014; Shang *et al.*, 2017). The spectrum emitted by white LED lights contain photons with energies that exceed the threshold of the enzymes serving as a stress-induced protection mechanism (Behar-Cohen *et al.*, 2011); thus, exposure to optical radiation from white LEDs may result in severe damage to the outer retina at high levels of exposure. Spectral power distribution (SPD), as well as irradiance, are risk factors that contribute to the photochemical retinal injury. To prevent or decrease this potential retinal damage, some companies are increasing the market segments of lower colour temperature (i.e. lower blue component) LEDs for domestic lighting (U.S. Department of Energy 2012).

Recently the potential for retinal damage from optical radiation emitted by 10 commercially available LED light sources and a LED lantern used for home was evaluated (James *et al*., 2017). Each lamp was tested by measuring the spectral irradiance and spectral radiance. The authors concluded that all light sources tested are in the exempt group according to the ANSI/IESNA Recommended Practice RP-27 series of documents (ANSI/IESNA 2005, 2007) which is the equivalent of the European Standard EN 62471 and therefore do not pose an ocular hazard.

6.5.3 Potential effects on the non-healthy eyes

Age-related macular degeneration (AMD) is a multifactorial disease and a leading cause of blindness in the patients aged about 65 years or older in industrialised countries (Chu *et al.*, 2013; Wu *et al.*, 2014).

The typical pathology of advanced AMD is described as having two main forms: geographic atrophy (GA) and neovascular (exudative) AMD. Although pharmacologic treatment has changed the visual prognosis of exudative AMD, there is still a limited curative treatment for AMD, and therefore the best option is to prevent its onset by trying to point out possible risk

factors which might contribute to further acceleration of the pathologic senescence process of the choroid, RPE and neuroepithelium. A growing number of studies indicate that the effect of oxidative stress contributes to AMD-related pathological changes (Beatty *et al.*, 2000; Lau *et al.*, 2011; Narimatsu *et al.* 2013). Besides aging and smoking, the main source of oxidative stress can be cumulative light exposure, which may induce abnormal accumulation of reactive oxygen species in the macula.

A systematic review and meta-analysis revealed that individuals with high levels of sunlight exposure (UVR exposure, visible light exposure and blue light exposure regarded as sunlight exposure) are at a significantly increased risk of AMD (Sui *et al.*, 2013). Furthermore, the risk for cataract extraction, as well as early AMD, is increased in subjects exposed to sunlight (Delcourt *et al.*, 2014). The cornea and natural crystalline lens absorb the most UVR (100 nm-400 nm), and only a small fraction of UV-A (315 nm-400 nm) reaches the retina (Sliney, 2001). Although by 20 years of age only 0.1% UVR reaches the retina, due to the metabolites of tryptophan which absorbing UVR (Sliney, 2002), another important component of sunlight, blue light has a better ocular penetration than UVR and by the age of 60–70 years old, there is still 40% of blue light (460 nm) reaching the retina (Behar-Cohen *et al.*, 2011).

The urban population tends to have longer duration of exposure to artificial lighting indoors rather than sunlight outdoor. However, for even a short period of time outdoors, the optical radiation exposure from sunlight tends to dominate.

6.5.4. Vulnerable and susceptible populations

6.5.4.1. Children

The transmission of UV-A and blue light to the retina is higher in young children than in older children (above about three years) and adults. The ICNIRP guidelines (ICNIRP, 2013) suggest that the action spectrum for aphakes may be appropriate for young children, generally considered to be those below about three years of age. This formed the basis of a recommendation on the emission limits for LEDs incorporated into toys (Higlett *et al.*, 2012).

6.5.4.2. Adolescent

The studies of Kim *et al.* (2016) show that smartphone use has dramatically increased in recent years. According to the authors, smartphones may have adverse health effects, particularly on the eyes, because users stare at the screen for a much longer time than with previous generations of mobile phones. The objective of this study was to elucidate the relationship between smartphone use and ocular symptoms among adolescents (n=715). The conclusion was that the increasing use of smartphones can have a negative impact on ocular health in adolescents, although there was no implication that the optical radiation had any direct adverse health effect.

6.5.4.3. Elderly population

No peer-reviewed studies were identified that suggested there was a specific risk to the older population from exposure to the optical radiation from LEDs. However, the aging eye transmits less blue light to the retina and is more susceptible to scatter light at these wavelengths.
There have been claims that blue-rich sources of light produce more glare for the older population. This is likely to be evident for LED displays (for example destination indicators on the front of buses) using blue light and vehicle LED lighting.

Conclusion

Although there are no reliable data to be used for risk assessment of eye-safety of life-time usage of LED light sources, there might be some concern on the potential negative consequences of LED emissions particularly in a susceptible population which already present early signs of pathologic senescence of the macula. However, it should be emphasised that those concerns derive from results obtained in experimental animal models or cell culture models using exposure levels greater than those likely to be achieved with LED lighting systems in practice.

Exposure to optical radiation from white LEDs may result in severe damage to the outer retina at high levels of exposure. Spectral power distribution (SPD) and irradiance are risk factors that contribute to the photochemical retinal injury. To prevent or decrease this potential retinal damage lower blue component LEDs for domestic lighting should be used.

6.6. Skin optics fundamentals

6.6.1 Structure of the skin

Human skin is constituted by three main layers: epidermis, dermis and sub-cutaneous tissue, made from different cellular types that fulfil different functions (see Annex II for a short description for the various parts).

Fitzpatrick (1975) originally developed a scale of skin types for use in phototherapy treatment planning. The scale has been more widely adopted (Fitzpatrick 1988) to indicate the sensitivity of the skin to ultraviolet radiation – see Annex III.

6.6.2 Optical properties of skin

Optical properties of the skin are complex, and result from reflectance; absorption and scattering of the different wavelengths of incident light (see for review Anderson and Parrish, 1981, Lister *et al.*, 2012, Liu, 2012). The optical pathways in the skin are shown in figure 8.

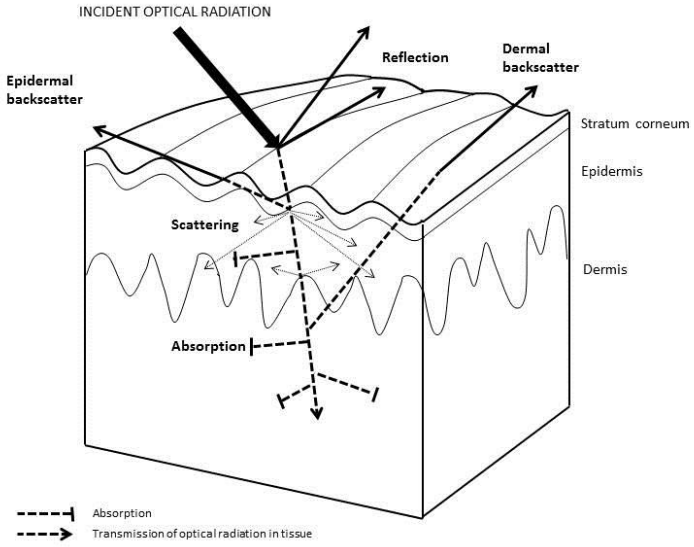

Fig. 8: Optical pathways in the skin (source: E. Bruzell)

Due to the change in refractive index between air (n_D = 1.0) and epidermal surface (n_D = 1.55 for the stratum corneum), a small fraction of incident optical radiation is reflected. This regular *reflectance* from normal skin is always between 4% and 7% over the entire spectrum from 250-3000 nm, for both white and black skin. Similar air-tissue optical interfaces also cause internal reflections of diffuse and back-scattered radiation, within the epidermis and dermis, and also contribute to *remittance* of the skin.

Absorption is a reduction in light energy. Absorption results from the presence of chromophores in the skin: urocanic acid, melanin, haemoglobin (oxy-/deoxy), bilirubin, porphyrins. Although abundant in all tissues, water is not a significant absorber of light in the visible region, but absorbs infrared radiation. Two molecules are the major light absorbing substances in skin: melanin and haemoglobin. Melanins, both eumelanin (brown) and

phaeomelanin (red) almost exclusively located in the epidermis in humans, have an absorption spectrum that gradually decreases from the ultraviolet (UV-B, 280 nm) to the near infrared (750 nm) regions. Haemoglobin is the dominant absorber of light in the dermis. The absorption spectrum of oxy-haemoglobin shows three peaks: a dominant peak in the blue region (420 nm) and two further peaks in the green-yellow region (500-600 nm), at respectively 540 and 580 nm [the combination of the blue and green-yellow bands cause haemoglobin to appear red].

Scattering is a change in the direction, polarization or phase of light and results from either a surface effect (such as reflection or refraction) or from an interaction with molecules/particules whose optical properties differ from their surroundings (particulate scatter). The major sources of particulate scatter in the skin are the filamentous proteins: keratins within the epidermis, and collagens in the dermis. In addition, other structures/substances such as melanosomes in the epidermis contribute to light scattering in the skin. Scattering is influenced by the size of the filaments; it increases with increasing fibre diameter, and with wavelength (it increases with decreasing wavelength).

Epidermis – the epidermis has an important function in absorbing most of the short-range UV-B (280-315 nm) and a significant proportion of UV-A (315-400 nm) radiation. This results both from absorption of UV radiation by melanin and urocanic acid, and from scattering by keratins. An efficient protection against UV is afforded by the thickening of the stratum corneum that results from the epidermal hyperplasia triggered by UV exposures.

Dermis – the dermis is mainly constituted from collagens and elastin and is highly vascularized. Light is absorbed by haemoglobin and scattered by the large collagen fibres (about 10 times larger than keratin fibres of the epidermis).

Sub-cutaneous tissue – the sub-cutaneous tissue is rich in fat and is vascularized. Fat is a highly diffusing optical medium, and haemoglobin absorbs light in blood vessels. But penetration of visible light (400-700 nm) in the skin is limited to a depth of about 3 mm, and only a small proportion of visible light penetrates sub-cutaneous tissue.

6.6.3 Penetration of light in the skin

The penetration depth of light in the skin is a function of wavelength and absorption/scattering by skin composition (melanin, keratin, collagen, haemoglobin, fat).

UV – Most UV-B incident on the skin is blocked by the epidermis. It is usually considered that only 10% of UV-B reaches the basal layer of the epithelium as opposed to 50% of UV-A. UV-A reaches the dermis.

Visible light – Penetration of visible light in the skin increases with increasing wavelength. However, penetration of visible light is limited to 0.8 – 3 mm.

Infrared – infrared radiation can reach subcutaneous tissue.

When optical radiation reaches a tissue, part of this radiation is scattered in the environment (5-7% for perpendicular radiation, and almost constant for all wavelengths) (Sandell *et al.*, 2011), some is absorbed in different layers, and part is transmitted internally by successive layers of tissue until the incident energy is dissipated.

The first optical interaction with skin occurs on the stratum corneum layer at the surface, where a certain fraction of the incident radiation is scattered in the environment because the corneal refractive index (n_p = 1.55) is much greater than air. This component represents 5-7% for radiation perpendicular, and is almost constant for all wavelengths.
The remission (diffusion reflectance) is the fraction of incident radiation that returns from the skin.

The transmission is the fraction of incident radiation that penetrates through the skin.

Regular reflectance is the radiation that penetrates the skin and is scattered back later (Sandell *et al.*, 2011). The absorption spectra of any tissue, including skin, is determined by the presence of all biologically important molecules involved in double bonds (chromophores of skin) and containing water in biological tissues. The overall optical properties of the skin depend on photon absorption and scattering by a wide range of biomolecules, with specific chromophores, of endogen or exogen origin: bilirubin, beta-carotene, aromatic amino acids (tryptophan, tyrosine), urocanic acid, nucleic acids and melanin. The major contribution to blood optical absorption is due to haemoglobin, both in its oxygenated and deoxygenated forms. Oxyhaemoglobin has an absorption band near 405 nm (Soret band) and the characteristic double peak absorption in the area of 545–575 nm; deoxyhaemoglobin strongly absorbs near 430 nm and a weak band at 550nm (Anderson *et al.*, 1982; Parrish and Jaenicke 1982; Cheong *et al.*, 1990)

The aminoacids have absorption maxima around 275 nm, the nucleic acids with maximum absorption in the 260 nm due to chromophores observed in the epidermis and cornea (see figure 9).

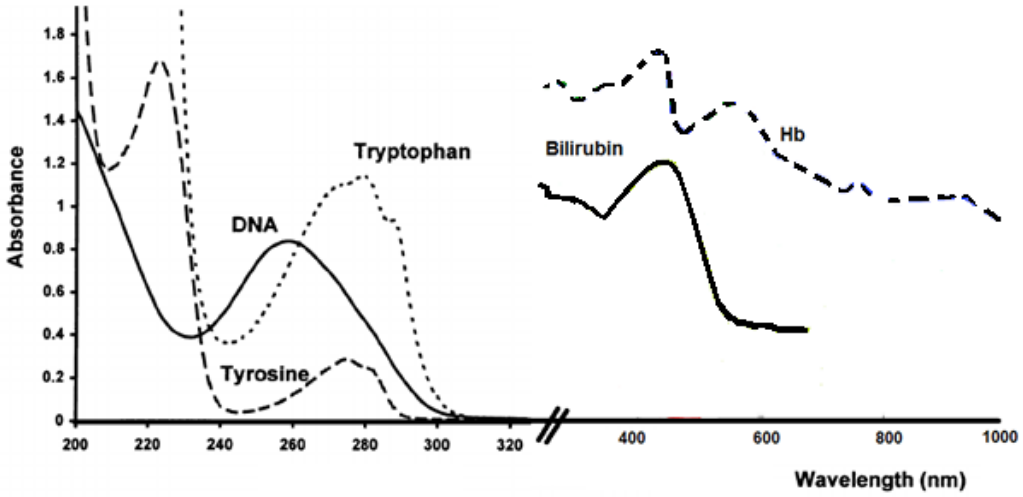

Fig. 9: The absorption spectra of different biological chromophores from human skin (source: R.M. Ion)

Melanin is the chromophore of the human skin epidermal layer and is one of the major light absorbers in some biological tissue. There are two types of melanin: eumelanin which is black-brown and pheomelanin which is red-yellow. Their absorption spectra are wide, without specific peaks and they effectively absorb in all spectral regions from 300 to 1200 nm. In the near-ultraviolet radiation and visible regions of the spectrum, except the melanin, the basic skin chromophores are bilirubin, vitamins, flavins, flavin ferments, carotenoids, phycobilins and phytochrome, among others, as well as elastin and collagen fibers (Utz *et al.*,1993).
The skin consists of three main visible layers from the surface: stratum corneum (~20μm thick), epidermis (100μm thick, the blood free layer), dermis (1–4 mm thick, vascularized layer). The average scattering properties of the skin are defined by the scattering properties of the reticular dermis because of the relatively large thickness of the layer (up to 4 mm) and of the comparable scattering coefficients of the epidermis and the reticular dermis (Genina and Tuchin, 2011).

The subcutaneous adipose tissue (1-6 mm thick depending from the body site) has absorption defined by absorption of haemoglobin, lipids, and water (about 11%) (Jacques, 2013).

At wavelengths from 600 to 1500 nm, scattering prevails over absorption and penetration depth is increased to 8–10 mm.

According to Johnson and Guy (1972), for a sample consisting of the epidermis and dermis, the depth of penetration is 0.15–0.2mm (wavelength 632.8 nm) and 0.21–0.4 nm (wavelength 675 nm).

6.7 Optical radiation effects on skin

The topic is reviewed in the SCENIHR Opinion "Health Effects of Artificial Light" (SCENIHR, 2012). A brief version containing some new information published since 2012 can be found in Annex III.

The SCHEER is unaware of UV-LED sources intended for the general population with the exception of a few devices for certain cosmetic purposes (see Annex III). UV nail lamps and/or LEDs do not appear to significantly increase the lifetime risk of non-melanoma skin cancer. However, data are lacking regarding the possibility of premature skin ageing, and the risk to the eyes of the professional operators should be considered. Assessment of LED sources in medical devices and for occupational use is beyond the scope of this Opinion.

Vitamin D production in human skin following exposure to UV irradiation from LEDs has been studied in vitro via High Performance Liquid Chromatography indicating possibility for synthesis of vitamin D2 and vitamin D3 if the UV LED source is powerful enough. However, UV-B is carcinogenic to humans and public health organizations, including SCHEER (SCHEER, 2016) do not recommend use of artificial UV radiation to enhance vitamin D levels

6.7.2 Effects of LED reported in the literature (photodermatoses)

6.7.2.1Controlled studies: A controlled study (Fenton *et al.*, 2013) investigated photosensitivity after exposure to either a single-envelope compact fluorescent lamp (CFL) (15 W GE BIAXTM Electronic 220–240 V; 50/60 Hz; 120 mA; FLE TBX/XM827 183 JA/S; 900 lumen), a double-envelope CFL (15 W OSRAM DULUXSTAR Mini Ball 827 Lumilux Warm White 220–240 V; E27; 50/60 Hz; 850 lumen) or an LED lamp (10 W 0026172 Hi-Spot RefLED PAR30; E27; 15 000 h; 100–250 V; 50–60 Hz; 20 lm Warm White 830/3000 K; 400 lumen). The emission spectra of the lamps between 250-400 nm at the distance of patient testing were recorded and presented. Two hundred patients (103 actively photosensitive) were exposed to the single-envelope CFL and of these, 11 patients were exposed to the double-envelope CFL. One hundred and one patients (45 actively photosensitive) were exposed to the LED and, in addition, there were 20 healthy controls. The patients were exposed on untanned skin on the inner forearm while the healthy controls were exposed on untanned skin on the back. All subjects were at a distance of 5 cm from the lamp. One of the exposure sites was covered with UVR-protective film. In the CFL-group 32 patients presented with responses (delayed papules, erythema and immediate urticarial responses), while in the LED-group one patient showed a response. Two of the healthy volunteers showed a positive erythemal response 24 h post-irradiation. The patient showing a positive response in the LED-group was diagnosed with solar urticaria and had visible light sensitivity. The SCHEER notes that the LED irradiance in the full emission range was unknown. The LED's UV emission was negligible compared to those of the CFLs.

A pilot study (Fenton *et al.*, 2014) investigated the exposure of a compact fluorescent lamp (CFL) (GE BiaxTM Electronic, part number FLE15TBX/XM/827, 220–240 V, 50–60 Hz, 15 W, 120 mA, 900 lumen (GE Lighting, Northampton, U.K.), an energy-efficient halogen lamp (EEH) (Osram Halogen ES Classic Spot R63, part number 64546 R63 ES, 240 V, 42 W, 630 lumen (Osram, Munich, Germany) and an LED (Hi-Spot RefLED PAR30, part number 0026172, 100–250 V, 50–60 Hz, 10 W, 400 lumen (Sylvania, Raunheim, Germany). The emission spectra of the lamps between 250-400 nm at the distance of patient testing were recorded and presented. Fifteen patients with lupus erythematosus (LE) and five healthy volunteers were included and tested for cutaneous responses to repeated exposures from the lamps. The patients were exposed on untanned skin on the back at a distance of 5 cm from the lamp. One of the exposure sites was covered with UVR-protective film. The authors reported that: "No cutaneous LE lesions were induced by any of the light sources. Delayed skin erythema was induced at the site of CFL irradiation in six of the 15 patients with LE and two of the five healthy subjects. Erythema was increased in severity and was more persistent in patients with LE. One patient with LE produced a positive delayed erythema to the EEH. A single patient with LE produced immediate abnormal erythemal responses to the CFL, LED and EEH. Further investigation revealed that this patient also had solar urticaria. All other subjects had negative responses to LED exposure". The SCHEER notes that the LED irradiance, for which UV-emission was negligible compared to those of the CFL and EEH, in the full emission range was unknown.

6.7.2.2 Case reports

A case of solar urticaria triggered by LED-therapy was reported by Montaudié *et al.* (2014). A 55-year-old woman with no history of urticarial rash following previous sun exposures was treated with 415 nm LED for mild rosacea (a photo-aggravated dermatosis). Phototesting confirmed the diagnosis of solar urticaria. The SCHEER notes that the irradiance, treatment distance and LED-spectrum were not noted.

A case was reported of a patient with cutaneous lupus erythematosus (CLE) who presented with a rash after dental treatment (Tiao *et al.*, 2015). The patient was allegedly being exposed to "surgical light" emitting UV-B, a wavelength range without purpose for this type of light. The SCHEER notes the spectral characteristics of the source were not given. It is unknown whether her reaction alternatively could have been due to an (photo-)allergy to dental materials, heat effects from the emission of blue light from LED dental curing lights (irradiance typically in the order of thousands mW/cm^2) or a drug-mediated photosensitivity reaction (the patient took several medications for her disorder).

6.7.3 Conclusions

Emission from commercial LED lighting can induce a positive skin response in some patients with solar urticaria when exposed in short distances in controlled environments. The dose that elicits such a response is not known.

The SCHEER concludes that thermal effects from visible and IR-emitting lighting sources are unlikely to cause adverse health effects in healthy skin from LEDs intended for lighting purposes and displays. However, there may be effects due to excessively intense sources close to the source, such as from high irradiance (near-) IR sources. If saunas and warming cabinets are equipped with IR-LEDs, these devices may cause erythema below the pain limit.

The SCHEER is not aware of UV-LEDs in tanning equipment, but such devices would have the same carcinogenic potential as conventional sources provided the same level of irradiance is received as from the radiation sources that the UV-LEDs have replaced. Cancer is not likely to develop from nail-curing LED-devices if the risk is not already increased in susceptible individuals.

6.8 Circadian rhythms

Apart from influencing vision, light received by our eyes has several non-image forming functions, such as the pupillary light reflex and providing input to our biological clock. The presence of a light (day) and dark (night) phase due to the earth's rotation has resulted in the evolution of an internal clock in almost all organisms, including humans. The rhythm imposed by this 'biological' clock has a periodicity of approximately 24 hours and is, therefore, often referred to as the circadian rhythm (circa = approximately, and diem = day). This biological timekeeping system imposes day-night rhythms on many processes in our body, including behaviour (sleep/wake cycle), endocrine regulation, immune response and energy metabolism. Disturbances of our circadian rhythms have been linked with negative effects on health and increased accident risks. The biological clock is highly influenced by external light clues, including artificial light. These results were previously reviewed in the SCENIHR Opinion 'Health effects of artificial light' in 2012. In the current Opinion, the SCHEER focusses on the effects of LED sources. For a summary of the mechanism of generation of circadian rhythms and their normal functions, see Annex V.

6.8.1. Synchronisation and regulation of the circadian rhythm by light

The central clock in our brain needs to be synchronised with the outer world, which occurs via light cues. In the absence of any light cues, the central clock will maintain its 'own' rhythm, which is usually a bit shorter or longer than 24 hours. After a few days, the circadian rhythm of a person would be 'out of sync' with the outside world (Dijk and Archer 2009; Dibner, Schibler *et al.* 2010). The peripheral clocks are synchronised by multiple cues, including neuronal and hormonal signals from the central clock, but also feeding time is an important cue for several peripheral tissues (Patton and Mistlberger 2013).

Multiple photosensitive receptors in the retina translate the light signal into a neuronal signal (see next section for more details). The influence of light on the circadian system is dependent on 1) timing, 2) intensity, 3) duration, 4) spectrum of the light stimulus, and 5) of previous light exposure. For intensity and duration, experiments have shown that there is a dose-dependent relationship with response of the circadian system (Duffy and Czeisler 2009). Importantly, relatively low intensity levels (<100 lux) and short durations (seconds to minutes) have been reported to affect the circadian system (Glickman, Levin *et al.* 2002, for review see Duffy and Czeisler 2009, Lucas, Peirson *et al.* 2014). With regard to timing and previous light exposure, light stimuli have a greater impact on the circadian system when they are present during the dark phase. Light present during the late night/morning will advance the phase of the circadian rhythm, whereas light present during the evening will delay the phase of the circadian rhythm. This is an important concept considering disturbances of the circadian rhythm since chronic light exposure during the evening, causing a phase delay, can result in social jetlag (see 6.9.4: 'Consequences of disturbance of the circadian rhythm by light'). Furthermore, the effect of light is dependent on previous light exposure, since adaptation to light also occurs with regard to the circadian system (Duffy and Czeisler 2009, Kozaki *et al.* 2016). Finally, the photoreceptors are not equally sensitive to all wavelengths of light; therefore, the spectrum of the light is critical.

6.8.2 Role of light spectrum on regulation of the circadian rhythms

Different wavelengths of light appear to have different effects on the biological clock. This is caused by the spectral sensitivity of the photoreceptors in the retina providing the input to the suprachiasmatic nucleus (SCN) via the intrinsically photosensitive retinal ganglion cells (ipRGCs). The photoreceptors of the retina include the rods and cones for image-forming vision. However, in the absence of rods and cones, several non-image forming functions remain (circadian entrainment, pupillary light reflex), indicating the presence of an additional photoreceptor. Melanopsin was discovered about 15 years ago as the protein in intrinsically photosensitive retinal ganglion cells of the retina (ipRGCs) that is responsible for providing input to the circadian system and providing other non-image forming functions (Hattar, Liao *et al.* 2002, Duffy and Czeisler 2009, Hatori and Panda 2010, Tosini, Ferguson *et al.* 2016). *In vitro* experiments have shown that melanopsin has a peak spectral sensitivity of around 480 nm (Panda, Provencio *et al.* 2003, Panda, Nayak *et al.* 2005, Qiu, Kumbalasiri *et al.* 2005, Torii, Kojima *et al.* 2007, Bailes and Lucas 2013). However, *in vivo*, the signals received in ipRGCs from the other photoreceptors also have a role in determining ipRGCs output and the subsequent input to the circadian system. Their relative contribution is still under investigation, which is compounded by the finding that this appears to be context dependent (Lucas, Peirson *et al.* 2014). Additionally, the spectral composition of the light that is received by the photoreceptor is influenced by the spectral transmission properties of the ocular media, which is, for example, dependent on age (Lucas, Peirson *et al.* 2014, Gimenez, Beersma *et al.* 2016). In summary, spectral sensitivity of the circadian system is a complex interplay of external and internal factors, and not yet completely understood. However, experiments have shown that, overall, circadian rhythms are more affected by short wavelength light (460-490 nm) (Duffy and Czeisler 2009, Benke and Benke 2013), with the exact peak probably dependent on the individual and context involved.

6.8.3 Influence by optical radiation including LEDs

For details on how human circadian rhythms are investigated in most of the described studies (such as assessing melatonin rhythms) please see Annex V. As described above, the circadian system is regulated by light input. The circadian system is not only influenced by daylight, but also by optical radiation from artificial light sources. Some artificial lighting sources influence aspects of the circadian system and compete with natural light as a zeitgeber. For example, studies using exposure to artificial light sources reported effects on melatonin rhythms and subsequent sleep (for example, Wright, Lack *et al.* 2001, Wright, Lack *et al.* 2004, Cajochen, Frey *et al.* 2011, Wood,

Rea *et al.* 2013, Chang, Aeschbach *et al.* 2014, Gronli, Byrkjedal *et al.* 2016, Rangtell, Ekstrand *et al.* 2016). This might have health consequences when artificial light is present during evening and night time, when naturally no light is present. Exposure to light during the evening and night may delay the phase of the circadian clock. This delay might cause a disturbance of the circadian rhythm: see section 'Consequences of disturbance of the circadian rhythm by light' in Annex V for more details. These effects can occur with all types of artificial light, however, recent studies indicate that this effect is amplified for certain types of LEDs which have relatively high amount of short-wavelength emission. As described above, the circadian system is more sensitive to light of a short wavelength.

6.8.3.1 Disturbance of the circadian rhythm by LEDs sources

The widespread use of LEDs is relatively recent. Therefore, only a small number of studies investigated the effects of LEDs vs. traditional light sources on circadian rhythms. It is important to note that LEDs, as traditional light sources, are not one homogenous class; their influence on the circadian system depends on the specific properties of that particular light source. Some studies have investigated the effect of (blue) LEDs on circadian rhythms without a comparison to traditional light sources (for example, Wright, Lack *et al.* 2004, Kayaba, Iwayama *et al.* 2014), which indicated that LEDs that emit short-wavelength light influence circadian rhythms, as do other light sources with short-wavelength light.

Most of the few studies available investigated screens illuminated by LEDs. For example, a study from Cajochen *et al.* investigated the effect of exposure to white light from a commercially-available screen illuminated with LEDs or a cold cathode fluorescent lamp (CCFL) illuminated screen (Cajochen, Frey *et al.* 2011). Spectral measurements were performed showing that the radiance between 400 nm and 480 nm of the LED screen was higher (0.241 W/(sr m^2) compared to 0.099 W/(sr m^2)). Participants were asked to watch this screen in a controlled laboratory setting for 5 hours during the evening. Relative to the non-LED screen, the LED screen delayed the dim light melatonin onset (DLMO) and enhanced the suppression of evening melatonin levels for approximately 2 hours. In addition, exposure to the LED screen reduced subjective and objective measures of sleepiness and increased performance on cognitive tasks, relative to the non-LED screen. These results indicate that exposure to screens illuminated with these types of LEDs have a larger immediate influence on the circadian system than the CCFL-illuminated screen.

A study from Wright *et al.* similarly showed that LEDs can phase delay the circadian rhythm in melatonin levels (Wright, Lack *et al.* 2001). However, in this study the phase delay caused by this type of white LED was not different to the phase delay caused by a traditional white fluorescent light source. In this study, a blue/green LED was also included, which did affect the circadian rhythm in melatonin to a greater extent compared to the white LED or white fluorescent light source. The authors report that the white LED has a narrow peak wavelength at 460 nm and a secondary broader peak wavelength at 560 nm. The blue/green LED has a peak wavelength at 497 nm and a half-peak bandwidth of 485-510. Exposure to the light sources was performed for 2 hours during night time (from 24.00- 02.00 h). Hence, exposure started when melatonin levels were already high. This is in contrast to the study by Cajochen *et al.*, where exposure was during the evening when melatonin levels start to rise and for a longer period (5 hours). All light sources suppressed the melatonin levels between 24.00 and 02.00 hours. In all experimental groups with an additional light source, a phase delay of the melatonin rhythm was observed the subsequent day. Exposure to light from blue/green LEDs caused the largest delay of 42 minutes. The delay observed after exposure to the fluorescent light box and white LEDs was similar (both 22 minutes). In summary, this study shows that all of the used light sources influenced the circadian rhythm of melatonin with the blue/green LEDs having a greater effect.

Similar findings were observed in a second study in which exposure to light from blue LEDs was compared to white fluorescent light (West, Jablonski *et al.* 2011). A white LED source was not included. Results show that there is increased melatonin suppression with increased radiance from blue LED light. Additionally, blue LEDs affect melatonin levels at lower radiances compared to white fluorescent light.

Combined, these studies indicate that any additional influence on the circadian system by LEDs is dependent on the characteristics of the emitted optical radiation and of the use of the LEDs (i.e. timing and duration) in a similar fashion as other light sources influence the circadian system. It is important to note that they might also have a more beneficial emission spectrum compared to traditional light sources (Aube, Roby *et al.* 2013, Lu, Chou *et al.* 2016) depending on the time (of the day) of exposure and on the characteristics of the LEDs.

Additionally, there are a few studies that investigated the effect of 'real life' devices in which LEDs are incorporated, such as tablets (Wood, Rea *et al.* 2013, Chang, Aeschbach *et al.* 2014, Gronli, Byrkjedal *et al.* 2016, Heo, Kim *et al.* 2016, Rangtell, Ekstrand *et al.* 2016). In these studies, no controls with non-LED devices were made. However, these studies provide some insight to the effects that occur in real life, where the use of screens illuminated by LEDs has increased tremendously over the recent years (Gradisar, Wolfson *et al.* 2013). Most of these studies observed effects on melatonin onset, levels, sleepiness and/or sleep quality. In one of the studies, no effects were observed (Rangtell, Ekstrand *et al.* 2016). The authors suggest that this might be due to bright light exposure during the day for 6.5 hours, however, no control group was included (Rangtell, Ekstrand *et al.* 2016).

The study by Chang *et al.* (2014) was the first to investigate repeated exposure to a LED illuminated screen on circadian rhythms. In this study, participants were asked to read a book using an iPad® or an ordinary book for 4 hours before going to sleep, for 5 consecutive days. The 'reading an ordinary book' is an important control group, since it controls for the level of (cognitive) activity performed regardless of light. Effects were observed on melatonin levels, time to fall asleep, subjective and objective sleep measures and sleepiness levels on the morning after. After 5 days of using the iPad® an average delay of the melatonin rhythm of 1.5 h compared to reading an ordinary book was observed on day 6. This observation is an important factor for the development of possible advice on health consequences.

In summary, the available studies indicate that white-light LEDs can have larger influence on the circadian rhythm compared to traditional light sources, due to their different spectral emission pattern. Light sources that emit more short-wavelength light, as do most white LEDs, will have a larger effect on the circadian system at equal intensity, duration and timing and after equal previous light exposure. However, recently new LEDs have become available that emit lower levels of short-wavelength light, which might decrease effects in the future, when use of these LEDs is more widespread. In addition, it is unclear if the effects on the biological clock remain with repeated exposure as occurs in real life. Furthermore, it is important to note that exposure to artificial light with high levels of short-wavelength during the day might enhance entrainment of the circadian clock.

6.8.4 Consequences of disturbance of the circadian rhythm by light

The studies described above showed that influence of artificial light sources on the circadian rhythm is dependent on the characteristics of the emitted optical spectral radiance. Several of the LEDs investigated in these studies have a larger effect on circadian rhythms compared to traditional light sources, due to their different spectral emission patterns. Currently, there are no studies that investigated the health

consequences of use of LEDs during the evening and night. For negative consequences reported for other artificial light sources, please see Annex V.

6.8.5 Vulnerable and susceptible populations

It is known that elderly persons have less robust circadian rhythms (Cornelissen and Otsuka 2016) and might, therefore, be more susceptible to circadian disturbance caused by artificial light in general. In addition, adolescents are known to more often have a late chronotype (Roenneberg, Kuehnle *et al.* 2007). Combination of a late chronotype with artificial light exposure during the evening might result in enhanced effects on sleep.

6.8.6 Conclusions

The currently available studies indicate that artificial light can influence the circadian system, depending on the light characteristics. Light sources that emit more short-wavelength light, as do some types of LEDs, will have a larger effect on the circadian rhythms at equal optical radiance, duration and timing of exposure. Exposure during the evening might result in poorer sleep and negative health risks, although evidence is limited. Several studies suggest a link between desynchronisation of the biological clock and increased metabolic risk factors. However, it is unclear if chronic artificial evening light can cause these effects.

However, the current conclusion is based on a limited amount of studies, which were mostly performed in a laboratory setting. An important question that remains is whether light from LEDs, and artificial light in general, present in indoor lighting and screens will have an effect on the circadian system in *real life* compared to natural light sources. Moreover, it is currently unknown if the effects on the circadian system remain, enhance or reduce, after repeated and ultimately after chronic exposure, such as currently occurs in real life.

6.9 Temporal Light Modulation (Flicker) and potential health effects

Most light sources operating from the electrical mains tend to have a degree of temporal modulation. However, sources such as incandescent lamps have thermal inertia, which means that the degree of modulation is limited to about 10%. LEDs operated from DC sources will not flicker unless modulation is introduced, for example to increase perceived brightness. LEDs operating from mains supplies (50 Hz in Europe) may have a degree of modulation ranging from less than 10% to 100%. Such modulation may also be introduced by dimming systems.

Flicker is usually used to represent modulation of the light source that can be perceived. Some people are susceptible to photosensitive epilepsy, which may be triggered by light modulation or rapidly changing images. The susceptibility is a function of flicker frequency and possibly the proportion of the field of view occupied by the actual or virtual source (which may include reflections from surfaces). Photosensitive epilepsy has an overall incidence of 1.5/100,000 per year, which increases between the ages of 7 and 19 years, to seven per 100,000 per year (Quirk et al., 1995). Concerns over exposure to flashing images on screens have existed since before the use of LEDs in screen technology (Wilkins et al., 2004). No published studies were identified to suggest increased reporting of symptoms as a result of LED technology. The usual trigger of concern for sufferers of photosensitive epilepsy is strobe-like lighting, as used in entertainment, or as experienced when driving through an avenue of trees with the sun to the side. However, there was one recent case study (Brna and Gordon, 2017) of an adolescent who had symptoms triggered by the multiple flash (to reduce "red eye") from a smart phone.

Under a flicker/strobe rate of about 5 Hz and above about 60 Hz, the proportion of patients with photosensitive epilepsy who are sensitive to an episode is less than 5%, with the peak sensitivity at about 20 Hz (Binnie et al., 2002).

Area lighting operating from the mains may flicker at 100 Hz (in Europe), which is above the frequency of concern for photosensitive epilepsy. However, depending on the degree of modulation, some people may perceive the flicker, especially in the peripheral field of view. Although no published case-studies were identified, there are claims that a small number of people are very sensitive to flickering light at about 100 Hz, triggering symptoms such as headaches, migraine and general malaise. The figure shows the LED lighting assessed in the home of a patient suffering from migraine and face burning when in the vicinity of their kitchen LED down-lighters (PHE, 2017). Figure 10 shows the lighting operating at full brightness (100%) and when set to 50% on a dimmer switch.

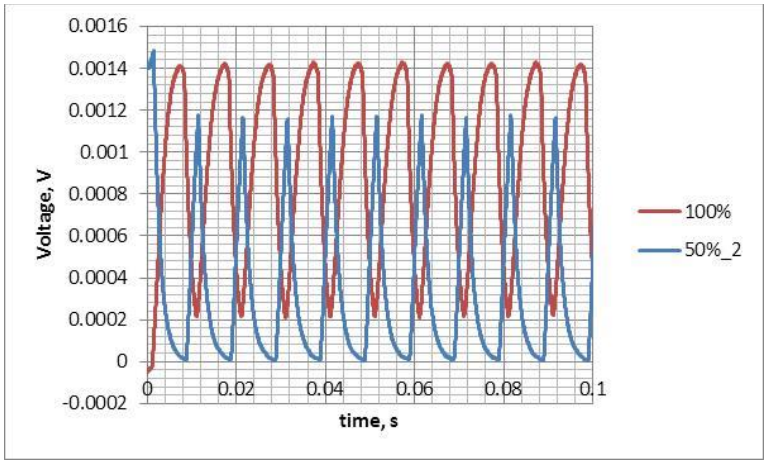

Fig. 10: Light emission as a function of time for an LED operating at full output and at the 50% setting on a dimmer switch

The spectra for the different LED lighting in the kitchen/dining room area is shown in figure 11.

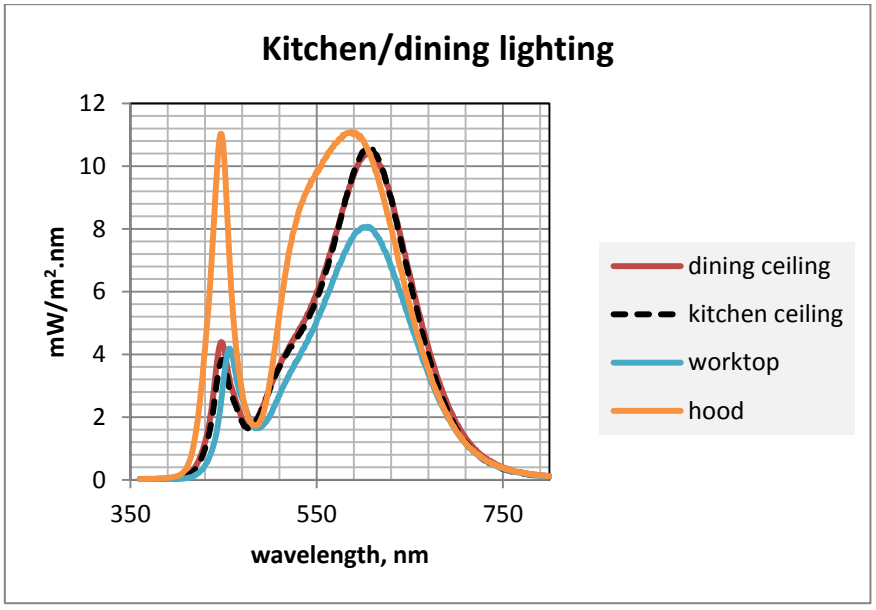

Fig. 11: Emission spectra for domestic LED installations in a kitchen

The Institute of Electrical and Electronics Engineers (IEEE) in the US published the IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers in 2015 (IEEE, 2015). This document provides a plot of the risk of adverse health effects as a function of frequency and percentage modulation.

As the flicker frequency increases, another effect is likely, called the phantom array. This is often experienced when travelling behind a car at night. If the car has LED brake or normal rear lights, a sudden eye movement can result in a series of images of the source. The effect can also be produced when driving past a static flickering light source, such as LED road studs (cat's eyes). Roberts and Wilkins (2013) showed that phantom arrays can be perceived at flicker rates up to about 2 kHz, and possibly higher under some circumstances for some viewers. It is possible that some of the susceptibility to high frequency (100 Hz and above) flicker may be due to the phantom array, even if the array is not perceived.

A major concern following the introduction of fluorescent lamps in industry was the stroboscopic effect, sometimes referred to the "wagon-wheel" effect, where a rotating object appears static. This was addressed in industry by ensuring that fluorescent lamps were on different phases and/or incandescent task lighting was used. LED lighting can produce the same effect, depending on the degree of modulation. However, of greater concern is the use of modulated LED lighting in domestic and other non-industrial environments where awareness is likely to be low. It is reasonably foreseeable that a food mixer blade could appear stationary when the only illumination source is a modulated LED, or a group of LEDs operating at the same frequency.

The International Commission on Illumination organised a workshop in February 2017 to consider the implications of temporal light modulation, and how to quantify both the hazard and the risk (CIE, 2017).

It is possible to operate LEDs from essentially DC power supplies. However, even when the temporal light modulation is assessed for a given LED luminaire, there appears to be no guarantee that similar luminaires, even with the same part number, will be identical (CIBSE, 2016).

6.9.1 Conclusion

LED lighting can produce a stroboscopic effect, depending on the degree of modulation. The use of modulated LED lighting in domestic and other non-industrial environments where awareness is likely to be low is of a concern. Although no published case-studies were identified, there are claims that a small number of people are very sensitive to flickering light at about 100 Hz, triggering symptoms such as headaches, migraine and general malaise.

6.10 Exposure and health risk scenarios

- Exposure situations in various indoor LED lighting settings

Many people spend significant proportions of the day and evening (and possibly night) staring at screens, which may be LED illuminated. Television screens tend to be viewed at distances of 1 metre or more, computer screens at about 50 cm and tablets or phones viewed at closer distances. There are also applications where a dedicated screen or a smartphone may be viewed within a few centimetres, for example in virtual reality headsets. O'Hagan *et al.* (2016) assessed the emissions from various screens and concluded that exposure levels were less than 10% of the ICNIRP blue light exposure limit, even for extended use durations. Since the assessment was carried out in terms of source radiance, the assessment conclusion was made independent of viewing distance.

The blue light photochemical retinal hazard to the eye from domestic LED lighting is between 10-20% (compared with 14% for a mid-range incandescent lamp) of the relevant ICNIRP exposure limit, assuming viewing longer than about 3 hours) (O'Hagan et al., 2016).

- Exposure situations in various outdoor LED lighting settings (streets)

Many street lights and other street fixtures are being converted to, or replaced with, LED lighting. The main driver for this is energy saving. However, if this factor alone is considered, LED lighting may be installed that is poor quality in terms of the optical spectrum, light pattern and glare.

Correlated colour temperature (CCT) is a measure of the blueness of an optical radiation source: the higher the CCT, the more blue-rich the source is. CCT is the temperature of a Planckian radiator that is the closest match to the emission of the source (CIE, 2011). The CCT of LED street lighting varies from about 7000 K down to about 2700 K. When compared with the sodium lamps that many LED street lights are replacing, the high CCT installations can appear harsh and almost equivalent to daylight. Moonlight has a CCT of about 4000 K, so it could be argued that artificial street lighting should not exceed this value. However, it is important that the lighting installation is appropriate for the use of the road (e.g., motorways may justify higher CCT lighting than residential roads).

Glare can occur from two main scenarios: the luminance may be too high or the luminance ratios are too high (IES, 2011). Good lighting practice is to ensure that unless it is the purpose of the source, the source should be diffused or shielded from direct viewing to avoid glare. Some LED street lights have exposed LED elements that can be seen by road users within their normal field of view, such as looking ahead. Such sources may contribute to discomfort glare (IES, 2011). Where the LED elements were recessed or diffused in order to reduce the luminance, such concerns were not reported.

Vehicle LED lights, and particularly daylight running lights and headlights, can be a source of either discomfort glare or disability glare. The latter is due to scattering of the light in the eye and is more prevalent for sources emitting high levels of blue light and for older observers. The sources may also produce a higher level of glare during fog. No references were identified with quantified assessments of these issues.

6.11 Overall conclusion:

The Committee concludes that there is no evidence of direct adverse health effects from LEDs in normal use (lightening and displays) by the general healthy population.

Either discomfort glare or disability glare can be temporarily caused by vehicle LED lights, and particularly daylight running lights and headlights.

Light sources that emit more short-wavelength light, as do some types of LEDs, will have a larger effect on the circadian rhythms at equal optical radiance, duration and timing of exposure. At the moment, it is not yet clear if this disturbance of the circadian system leads to adverse health effects.

7. RECOMMENDATIONS FOR FUTURE WORK

The review of the published research conducted by the SCHEER has led to valuable conclusions and identified certain gaps in knowledge on potential risks to human health from LEDs. These gaps could be partially filled if further research would be carried out to elucidate unresolved problems as follows.

Effect on the eyes

There is insufficient knowledge about the actual exposure of people to optical radiation from LED sources and the total exposure from all optical radiation sources – information about the exposure of the general healthy population is needed for assessing the potential health effects. It is suggested that the exposure assessments should consider different age groups, i.e. babies, young children, adolescents and adults into old age.

It was recognised that early-to-market LED lamps had a significant blue emission. Further research is going into improving LED lamps to make them similar to traditional types of lighting, such as incandescent lamps. The current EN 62471 standard does not take account of population groups particularly sensitive to blue light, hence there are no specific recommendations for population groups whose natural mechanisms for filtering blue light are diminished (children, aphakics and pseudophakics). However, it is recognised that the exposure of the general population to optical radiation from LEDs is likely to be insignificant compared with the exposure to natural light outdoors, but any additional health burden needs to be considered.

High luminance, flicker, phantom array and stroboscopic effect are other factors relevant to risk assessment that need to be addressed in further studies. In particular, are some population groups particularly susceptible to modulated emissions from LED lamps, either due to the design of the LED drive circuit or through the use of dimming circuits? The use of high luminance vehicle lighting should be investigated to determine if there are potential adverse consequences for increased accident rates.

Cumulative exposure over a twenty-four hour time period should be considered, and further research should be done into the reported effects of long-term, low-level exposure on age-related macular degeneration.

Effects on healthy skin

Depth of skin penetration is primarily dependent upon the wavelength of the optical radiation. Research should be carried out on heat effects on the skin and the relation to skin cancer, if the use of infrared saunas/warming cabinets incorporating infrared LED sources are established. In addition, exposure and dose levels for the induction of effects for patients with certain photodermatoses should be investigated.

Circadian system

An important question is whether optical radiation from LEDs, and artificial light in general, which is present in indoor lighting and screens will have an effect on the circadian system in *real life* compared to natural light sources. Research will need to consider the wavelengths of emission, time of day and duration of exposure, any confounding factors, such as the activity being carried out, prior light history and the age of subjects. Secondly, it is currently unknown if the effects on the circadian system remain, enhance or reduce after repeated and ultimately after chronic exposure, such as currently occurs in real life. Moreover, it remains to be investigated if the potential disturbance of the circadian system, caused by LEDs and/or artificial light, is related to negative health effects, as appear to occur due to other circadian disturbances such as shift work.

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9. GLOSSARY OF TERMS

Some basic performance characteristics, which can be used for comparing LEDs of the same or different technologies, are listed below:

Action spectrum	the rate of a physiological activity plotted against wavelength of light. It shows which wavelength of optical radiation is most effectively used in a specific chemical reaction. Action spectra are a necessary basis for finding the pigment(s) responsible or a specific photoresponse
Beam angle	the angle at which the brightness decreases to 50% of the maximum value. LEDs are directional light sources with an emission pattern, which is usually conical. (No light is emitted from the back of the LED.)
Blue light hazard	the potential for a photochemical-induced retinal injury resulting from electromagnetic radiation exposure at wavelengths primarily between 400 and 500 nm. The BLH mechanism overrules the thermal damage for long exposure times (more than 10 sec).
Blue light hazard irradiance	irradiance, spectrally weighted with the blue hazard (W/m^2)
Candela	The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×1012 hertz and that has a radiant intensity in that direction of 1⁄683 watt per steradian. The definition describes how to produce a light source that (by definition) emits one candela.
Correlated Colour Temperature	a specification of the colour appearance of the light emitted by a lamp, relating its colour to the colour of light from a reference source when heated to a particular temperature, measured in degrees Kelvin (K)
Degree of erythema	The minimal erythemal dose (MED), which is defined as the threshold UV dose for a minimal redening of the skin occuring a few hours after exposure, is typically 200-250 J/m^2 for phototype II after weighting with the CIE action spectrum for erythema. A standard erythemal dose (SED) is defined as 100 J/m^2 CIE erythemally-weighted UV.
Dose-response relationship	The dose–response relationship, or exposure–response relationship, describes the change in effect on an organism caused by differing levels of exposure (or doses) to a stressor after a certain exposure time
Electroluminescence	Optical phenomenon and electrical phenomenon in which a material emits light when an electric current pass through it

Electromers	one of two or more substances that differ only in the distribution of electrons
Exposure limits	It is important to note that to define the exposure limits, experiments were carried out on rabbits and some monkeys, exposed acutely to optical radiation (with different wavelength). Fundus examination was performed and the toxicity limit was reached when a white lesion was observed on the retina. Then, when this limit was determined, a reduction factor (between 2 and 10) was added. The blue-light hazard exposure limit is to protect against photo-maculopathy and is not based upon chronic light exposure. [Behar-Cohen *et al.*, 2011]
External quantum efficiency	is the quotient of the number of photons emitted out of the LED over the number of electrons passed in the device.
Feeding efficiency	is the quotient of the average ratio of photons emitted to the total energy acquired by an electron-hole pair from the power supply when the LED is operating.
Fluorescence	Emission of optical radiation, usually visible light, caused by excitation of atoms in a material, which then reemit almost immediately (in aprox. 10^{-8} seconds)
Forward currents	The current which flows across the LED's leads, from anode to cathode, in order for the LED to receive sufficient current to power on
Forward voltage	The forward voltage is the voltage drop across the diode if the voltage at the anode is more positive than the voltage at the cathode
Forward voltage drop	Is the voltage drop across a conducting, forward-biased, LED. It depends on the energy bandgap of the semiconductor material from which the diode is made as well as the series resistance of the material. LEDs are made to produce a variety of colours, using different materials and energy bandgaps. As an example, the forward voltage drop of red LEDs is around 2.2 V and the forward voltage drop for white/blue LEDs is in the range of 3.1 to 3.8 V [Kumar Khanna, 2014].
Glare	difficulty seeing in the presence of bright light such as direct or reflected sunlight or artificial light such as car headlamps at night.
High-brightness LED	Any of a new generation of LEDs bright enough for

	illumination applications such as automotive interior, exterior, and display
Illuminance	irradiance, spectrally weighted with the photopic eye sensitivity curve. The SI unit is lux.
Irradiance (exposure rate)	radiant energy per surface area per unit time in ($J/m^2s = W/m^2$).
Lumen	The standard unit for the luminous flux of a light source. It is an SI derived unit based on the candela. It can be defined as the luminous flux emitted into unit solid angle (1 sr) by an isotropic point source having a luminous intensity of 1 candela.
Luminance	A photometric measure of the luminous intensity per unit area of light travelling in a given direction. It describes the amount of light that passes through, is emitted or reflected from a particular area, and falls within a given solid angle. The SI unit for luminance is candela per square metre (cd/m^2)
Luminous efficacy	Is the quotient of the luminous flux emitted by the power consumed by the LED; it is measured in lumens/watt.
Luminous flux	The quantity of the energy of the light emitted per second in all directions. The unit of luminous flux is lumen (lm).
Luminous intensity	A measure of the wavelength-weighted power emitted by a light source in a particular direction per unit solid angle, based on the luminosity function, a standardized model of the sensitivity of the human eye. The SI unit of luminous intensity is the candela (cd)
Phosphorescence	The emission of light from a substance exposed to radiation which persists after the exciting radiation has been removed
Radiance	radiant intensity per area emitted from a source; in (W/m^2sr)
Radiant efficiency	the product of external quantum efficiency and feeding efficiency.
Radiant exposure	radiant energy per surface area in J/m^2
Radiant intensity	The radiant flux emitted, reflected, transmitted or received, per unit solid angle, and spectral intensity is the radiant intensity per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength.
Radiant power	Radiant power or **radiant flux** in radiometry is the radiant energy emitted, reflected, transmitted or

	received, per unit time, and spectral flux or spectral power is the radiant flux per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength.
Regular reflectance	The radiation that penetrates the skin and is scattered back later
Remission (diffusion reflectance)	The fraction of incident radiation that returns from the skin or from a particular sample
Singlet oxygen	The most energic state of oxygen generated by light excitation of the ground state of oxygen
Steradian	the unit for a solid angle, which is the 3 dimensional analogue of an ordinary angle. Any area on a sphere, which is equal in area to the square of its radius, when observed from its centre, subtends precisely one steradian (sr)
Transmission	The passage of electromagnetic radiation through a medium

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10. LIST OF ABBREVIATIONS

AC	Alternating current
AD	Atopic dermatitis
AK	Actinic keratosis
AMD	Age-related macular degeneration
ARM	Age-related maculopathy
BCC	Basal cell carcinoma
CAD	Chronic actinic dermatitis
CCFL	Cold-cathode fluorescent lamp
CFL	Compact fluorescent lamp
CI	Confidence interval
CIE	Commission International de l'Eclairage
CMM	Cutaneous malignant melanoma
CRI	Colour rendering index
DC	Direct curent
DNA	Deoxyribonucleic acid
ECDC	European Centre for Disease prevention and control
ECHA	European Chemicals Agency
EEH	Energy-efficient halogen lamp
EFSA	European Food Safety Authority
ELC	European Lamp Companies Federation
ELV	Exposure limit value
EM	Electromagnetic (radiation)
EN	European standards
EU	European Union
FED	Field emission device
FL	Fluorescent lamps
GaAs	Gallium arsenide
GLS	General Lighting System

HID	High-intensity discharge lamp
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ipRGCs	Intrinsically photosensitive retinal ganglion cells
IR	Infrared (radiation)
IR-A	The wavelength range of 780-1400 nm
LE	Lupus erythematosus
LED	Light emitting diode
LET	Lupus erythematosus tumidus
LPS	Sodium low-pressure lamp
LVD	Low Voltage Directive
LWS	Long wavelength cone opsin, Long wavelength sensitive cones (red)
MED	Minimal erythemal dose
MHL	Metal halide lamp
MWS	Medium wavelength cone opsin, medium wavelength sensitive cones (green)
NIR LED	Near Infra Red LED of wavelengths between 780 nm and 1400 nm
OLED	Organic light emitting diodes
OR	Odds Ratio
PDT	Photodynamic therapy
PLE	Polymorphic light eruption
PMLE	Polymorphous light eruption
POLA	Pathologies Oculaires Liées à l'Age (study)
PWM	Power wave modulation
ROS	Reactive oxygen species
RPE	Retinal pigment epithelial cells
RR	Relative risk

SAD	Seasonal affective disorder
SCC	Squamous cell carcinoma
SCCS	Scientific Committee on Consumer Safety
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
SCHER	Scientific Committee on Health and Environmental Risks
SCN	Suprachiasmatic nucleus
SED	Standard erythemal dose
SHP	Sodium high-pressure discharge lamp
SI	Système International d'unités (International System of Units)
SLE	Systemic lupus erythematosus
SSL	Solid state lighting
SWS	Short wavelength cone opsin, short wave length sensitive cones (blue)
TL	Tube luminescent (French for luminescent tube)
UV	Ultraviolet (radiation)
UV-A	The wavelength range of 315-400 nm
UV-B	The wavelength range of 280-315 nm
UV-C	The wavelength range of 100-280 nm
VUV	Vacuum ultraviolet radiation
XP	Xeroderma pigmentosum

ANNEX I LED Technolgies

Inorganic LEDs

The first LEDs in the 1960s were based on gallium arsenide (GaAs) crystals and emitted infrared radiation but no visible radiation, therefore, their applicability was limited. The introduction of phosphorus (P) in GaAs resulted in a red-light LED. Some of the most common semiconductor materials used for LEDs are listed in Table 2.

Table 2. Semiconductor materials used in LEDs and their resulting radiation (Gilbert, 2009)

Material	Radiation emission
Aluminium gallium arsenide (AlGaAs)	Red and infrared
Aluminium gallium phosphide (AlGaP)	Green
Aluminium gallium indium phosphide (AlGaInP)	Bright orange red, orange, yellow
Aluminium gallium nitrate (AlGaN)	Near to far ultraviolet
Diamond (C)	Ultraviolet
Gallium arsenide phosphide (GaAsP)	Red, orange and red, orange, yellow
Gallium phosphide (GaP)	Red, yellow, green
Gallium nitrate (GaN)	Green, emerald green
Indium gallium nitrate (InGaN)	Bluish green, blue, near ultraviolet
Sapphire (Al_2O_3) as substrate	Blue
Silicon carbide (SiC)	Blue

There are many variations of the basic technology that can enhance the efficiency of LEDs. The technology described above is based on a metallurgical interface formed between p- and n-doped semiconductors of the same material (homojunction). This can be replaced by materials of different energy bandgaps and/or polarity (heterojunction), so that the vast majority of photons produced are not reabsorbed in the LED materials and diffusion of electrons through the (shallow) p-region does not lead to non-radiative recombination at the interface.

Organic LEDs

Organic LEDs (OLEDs) constitute the evolution of inorganic LEDs. Their name originates from the use of organic semiconductors to achieve light emission. Organic semiconductors are organic compounds containing sequences of carbon (C) and hydrogen (H) atoms, with occasionally nitrogen (N), oxygen (O), sulphur (S), or other atoms fastened to this sequence. In a saturated organic material there is an electron pair responsible for holding the carbon atoms together. Therefore, all electrons are bound to atoms and the material is an electrical insulator. However, in an unsaturated organic material, excess electrons can exist in the carbon atom bonds, which are loosely bound to the carbon atoms. These electrons are called π-electrons and give the material the properties of a semiconductor by hopping, tunnelling and other charge mobility mechanisms. Organic semiconductors are considered an environmentally friendly technology and are biodegradable (Kumar Khanna, 2014).

Two types of electroluminescent materials are used for creating white OLEDs, namely, fluorescent and phosphorescent materials. Fluorescence is the emission of optical radiation (light) when a substance is exposed to any type of electromagnetic radiation, where the emitted radiation generally appears within 10 ns after the excitation. This

effect is due to an allowed transition generally from an excited singlet state to a ground singlet state. Phosphorescence is any delayed emission of optical radiation which appears 10 ns or longer after the excitation. This term should be used only for the delayed emission due to a forbidden transition from an excited triplet state to a ground singlet state.

The first OLEDs were fabricated by the deposition of small organic molecules on substrates. However, this technology poses a number of difficulties including the fact that it has to be implemented in vacuum. As a result, polymeric LEDs were developed and proposed as an alternative, even though they have a less efficient performance and a shorter lifespan compared to small-molecule OLEDs.

Some basic performance characteristics which can be used for comparing LEDs of the same or different technologies are listed below:

Comparison of different LEDs

Table 3 contains a comparison between inorganic and organic LEDs.

Table 3. Comparison between inorganic and organic LEDs (Kumar Khanna, 2014)

Characteristic	Inorganic LEDs	Organic LEDs
Operating voltage	Low	High
External quantum efficiency	High	Low
Maximum luminance	10^6-10^7 cd/m^2	10^2-10^4 cd/m^2
Glare effects	Possible	No (diffused light)
Lifetime	Long	Shorter (depends on environmental conditions)
Fabrication process	Complex	Simple

White light

White light is composed of several colours as seen in the rainbow. It is also possible to create white light by additive colour mixing. This method is based on the physiological response of the human eye, which usually is expressed by saying that human vision is trichromatic. The three additive colours (also called primary) that are used for creating other visible colours by mixing them in appropriate proportions are red, green, and blue (RGB). In this way, it is possible to create white light by using three LEDs emitting in the three primary additive wavelengths (colours). Nevertheless, there is a way to create a white perception by the eye using only two colours, known as a complementary pair. One colour of a complementary pair incorporates the wavelengths of a part of the visible spectrum, while the other encompasses the remaining range of wavelengths. Examples of complementary pairs are blue and yellow, green and magenta, and red and cyan.

The idea of complimentary pairs can help generate white light with a single LED, by the technique of wavelength conversion. The LED emits in a relatively narrow wavelength band compared to incandescent lamps. Some of the light emitted is absorbed by a phosphorescent material and re-emitted in a wavelength band in the residual spectrum. (The wavelength of the emitted photon by the phosphorescent substance is of longer wavelength than the absorbed one, an effect known as the *Stokes shift*.) As a result the initial light from the LED and the converted (in terms of wavelength) light from the phosphorescent material can be combined to produce white light.

White inorganic LEDs

There are no inorganic LEDs emitting white light, i.e., radiation of such a broadband spectrum. The two techniques described above are used for manufacturing "white LEDs". In the case of multichip LEDs, three or more LEDs, each emitting light in a narrow band (e.g., in red, green, blue) are used. If a single LED is used, then wavelength conversion has to take place. Some of the techniques employed to achieve this include: (i) Blue LED + yellow phosphor (= phosphorescent material); (ii) Blue LED + several phosphors; (iii) Blue LED + quantum dots (= nanocrystals 2-10 nm size containing cadmium or selenium atoms); (iv) UV LED + RGB phosphors.

Multichip LEDs have a higher efficiency compared with the single chip LEDs, since wavelength conversion is accompanied by energy loss in the phosphorescent material. However, since every LED requires its own power source to electronically adjust the light it emits, RGB multichip LEDs become expensive, as well as challenging in the design of the electronic circuits needed to drive them. Therefore, due to the lower cost and easiness of fabrication the most frequently method implemented to create white light is a near-UV or blue LED (InGaN-GaN) combined with a yellow phosphor (YAG:Ce).

White OLEDs (WOLEDs)

White organic LEDs use the same principles for synthesizing white light, like the ones described above. However, it is easier to fabricate a single LED with white electroluminescence with organic materials. The main approaches to obtain white light from organic/organometallic emitters are summarized in Fig. 12 (Farinola and Ragni, 2011). There are two general categories of methods as mentioned above: (a) combination of two or more individual emitters of different colours, (b) a single material that simultaneously emits different wavelengths covering a broad part of the visible spectrum. If the first approach is used, the emitters can be confined either in a single layer or stacked in a multilayer fashion. In the second approach a single compound can be employed that emits light at different wavelengths from molecules and their excited states (e.g., excimers or electromers). It is also possible to produce white light from one single polymer that contains different emitting moieties connected in the same molecular entity. The latter method offers the potential for low cost and large area light emitting devices but it poses the challenge of careful molecular design and arrangement, as well as precise control of the moiety ratios.

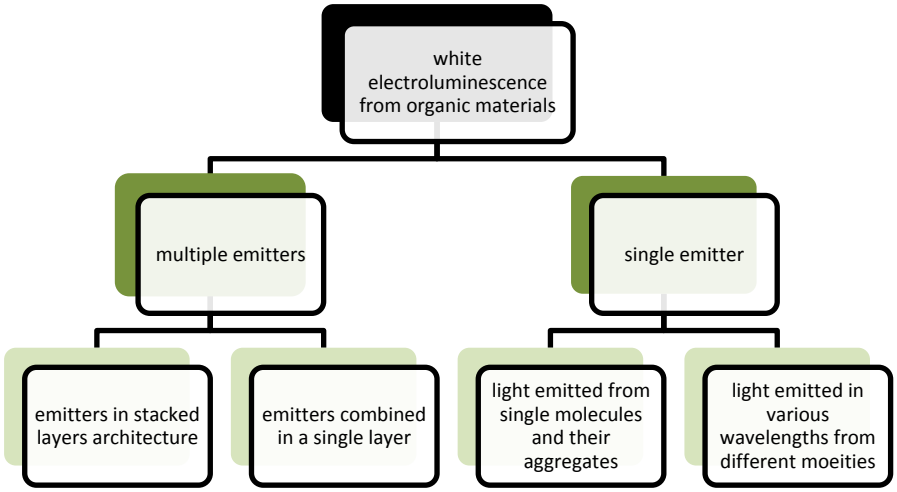

Figure 12. Methods to produce white light with organic/organometallic emitters (adapted from Farinola and Ragni, 2011).

Thermal management of LEDs

The physical processes that convert electrical energy to light result in the production of heat, which must be removed from the devices, because overheating reduces their lifetime. Moreover, changes in temperature affect the forward voltage of a LED and the wavelength of light emitted. For white light generation with additive colour mixing (RGB technique) such a change in wavelength can be detrimental, since stability is necessary to get the desired result. The efficient thermal management of light emitting diodes allows for higher forward currents and, thus, more light emitted by it.

Thermal management is performed with the use of materials with high thermal conductivity that permit heat to diffuse away from the LED to a heat sink. The latter is usually a plate or other structure of large surface made of copper, from which heat is removed by natural or forced convection. The design of the heat sink depends on the power supplied to the LED, the number of LEDs put together, as well as environmental conditions, like temperature and site of operation (e.g., open space or enclosure).

High-brightness LEDs

A high-brightness LED is one which gives a luminance flux of more than 50 lm (Kumar Khanna, 2014). A LED that consumes high power is not necessarily of high-brightness. The efficacy of a high-brightness LED is about 100 lm/W and the driving current is 350 – 1400 mA. Effective heat removal is crucial for high-brightness LEDs and this is usually achieved by a heat sink immediately next to the LED junction.

High-brightness LEDs are used for backlighting (e.g., phone LCDs), flashlights, general illumination, automotive daylight running/headlamps, signal lamps and medical devices.

Driving circuits of LEDs

One of the concerns, raised about LED lighting, has been flicker. LEDs can usually be operated from a DC source. However, for various reasons, products are manufactured that produce optical emissions with a degree of temporal modulation. The various options for drive circuits are described below.

DC Circuits

There are two methods for driving an LED with a DC source, namely a constant voltage source or a constant current source. The first method is more problematic to implement: forward voltage may differ among LED batches within a manufacturing tolerance. As a result, the current flowing in each LED, when they are aggregated in luminaires, becomes uneven. However, LEDs are non-linear devices, which mean that forward current changes drastically with small changes in forward voltage. This implies that uneven forward currents lead to dissimilar optical outputs from the LEDs with detrimental impact on the desired operation of the luminaire. Therefore, it is preferable to drive LEDs at a constant current.

There are mainly two techniques to achieve a constant current supply to LEDs, namely by using a resistor to limit the current flowing in the LED and by using a constant current source, like a DC-DC converter. Although current limiting resistors are an inexpensive solution to constant current sources, they suffer from important drawbacks. Resistors dissipate electric energy and generate heat, which is wasted power that needs to be removed. Moreover, using a voltage source and a resistor will not prevent the LED from experiencing voltage supply variations as current changes and, consequently, light output variations. Nor will it protect an LED from getting damaged by high voltage. Constant current supply suggests LED connection "in series" in a luminaire, a configuration where failure of one LED leads to a failure of the whole series of LEDs. Connection of LEDs "in parallel", which is inevitable in several cases either for single LEDs or for chains of them, still poses the problem, as discussed above, of equalising the current flowing in them.

AC circuits

DC driving of LEDs is an optimal approach for battery powered devices, like mobile phones. However, when it comes to luminaires that stretch several metres (e.g., around a building) DC drive can result in significant losses, like in the case of power distribution, requiring high voltages and additional current regulators. However, to run an LED directly from the AC supply will require the use of a transformer to reduce voltage and a rectifier to make it as constant with time as possible. The output of a full-wave rectifier converts the sinusoidal AC voltage of 50/60 Hz to a DC voltage pulsating at double the frequency. Due to the fast response of LEDs the small changes in the DC voltage are translated into flickering light. To solve this problem, a capacitor in parallel to the LED may be used.

One way for LEDs to operate connected directly to an AC supply is the "Christmas tree lights" approach, where the driving voltage equals the sum of all voltage drops across each LED, when several of them are connected in series. Using this approach, two strings of LEDs can be connected to the source, each one in reverse polarization. In this way, during the positive half-cycle of the AC voltage, current can flow through the LEDs of one string only, while during the negative half-cycle, current can flow through the LEDs of the other string. It is important to note that in this approach the (reverse) voltage applied to each LED of the non-emitting string should be low enough not to damage it.

Dimmers

LED dimming can be achieved either in an analogue or in a digital fashion. In the former case the forward current through the LED is varied, and so is the optical output. However, in this method heat is generated constantly, which may result in an undesired temperature change. Digital dimming is implemented with PWM (pulse width modulation), in which the forward current flows through the LED in a periodic pulsating manner for a fraction (duty cycle) of the total time cycle duration (comprising both on- and off-time intervals). As a consequence, the average current, which is related to the optical output, is different from the peak current. The pulsation of the forward current has to be performed at a rate (frequency) large enough, so that it is not perceived by the human eye either as a direct flicker or through a stroboscopic effect.

ANNEX II The fundamental interaction between light and matter

There are four basic interactions that can occur following absorption of optical radiation:

(a) **Photothermal:** partial conversion of light energy into heat motion via transitional, rotational and vibrational modes of movements of the target molecules. The effects are produced by the photoexcitation of tissue by the production of thermal energy (heat), accompanied by an increase of the temperature for the exposed tissue (Cicchi *et al.*, 2016). The most important and significant alterations are dependent on the temperature of the tissue after absorption of the optical radiation, as follows: at 37°C, no measurable effects are observed; for the next 5°C above this, the tissue is thermally affected due to conformational changes of molecules. Some bond destruction and membrane alterations occur at approximately 42-50°C, and at 60°C denaturation of proteins and collagen occurs leading to coagulation of tissue and necrosis of cells. At higher temperatures (>80°C), the cell membrane permeability is drastically increased.

(b) **Thermal relaxation**: is influenced by the thermal coefficient of the tissue, the properties of the surrounding tissue or fluids and the temperature differential between the irradiated and non irradiated tissue (Litvack *et al*., 1988). An example is the exposure to intense flashes of light shorter than ~20 μs (not likely from current LEDs); when the rise in temperature is at least 10°C above the physiological temperature, the thermal damage occurs, which leads to thermal denaturation of many proteins. Factors that influence thermal relaxation are summarized as follows: absorption characteristics of the target tissue; emission mode: continuous wave or pulsed emission; incident power; power density; beam movement relative to tissue site (for example, with a laser beam, rapid beam movement will reduce heat build-up and aid thermal relaxation); endogenous coolant: water content and vascularity of the tissue.

(c) **Photochemical interactions:** when the radiant energy causes atomic or/and molecular excitation. In the photochemical reactions, the molecule must absorb optical radiation and the radiation energy must match energy difference between the ground and excited state. Photochemical effects occur as a result of direct excitation of electronic bonds by the optical radiation (Litvack *et al.*, 1988). At shorter wavelengths, tissue components become electronically excited, thus this (photo excitation) leads to rupture of molecular bonds and formation of molecular fragments. Photochemical reactions generally do not result in a significant rise in temperature, but they are involved either a change in the course of biochemical reaction due to the presence of an electromagnetic field or photodecomposition due to high energy photons that rupture molecular bonds (Das, 1991; Monajembashi *et al.*, 1986; Niemz, 2004).

(d) **Photomechanical and photoelectrical interactions:** non-thermal interactions produced by high energy, short pulsed laser light, including: photodisruption, photodisassociation, photoplasmolysis and photoacoustic interaction. Absorption of pulses of energy result in rapid expansion or generation of shock waves responsible for photo-disruption or photodissociation. The laser beam's energy is transformed into vibration or kinetic energy (Harris *et al.*, 1989). Such interactions are not likely from current LEDs.

In conclusion, the light absorption can result in the formation of an (electronically) excited state, which has different chemical properties to the ground state. The intensity and shape of absorption spectra are a result of the nature of excitation between ground and excited states. Various processes result in the deactivation of the excited state. The energy could be lost through fluorescence or phosphorescence (emission of radiation of longer wavelengths) or dissipated as heat.

Photobiology

Photobiology is the study of the interaction of optical radiation with living organisms.

ICNIRP guidelines (ICNIRP, 2013) state that exposures to optical radiation can produce acute onset of observable biological responses. In general there is a lack of knowledge regarding the injury threshold for effects from long term chronic exposure. But, in contrast to the ICNIRP guidelines for electromagnetic fields with wavelengths greater than 1 mm, the guidelines for optical radiation in general do not differentiate between workers and the general public (ICNIRP, 2004; ICNIRP, 2013).

The time elapsed between the absorption and the biological effect is called the primary radiation effect period. Since optical radiation is absorbed in tissue, with penetration depths of a few microns for UV to millimeters for IR, it follows that it is the skin and eyes of the human body that are the most affected direct target tissues. The photochemical effects (i.e., chemical changes in target cells) dominate in the UVR and shorter wavelength visible spectral regions, while the thermal effects are dominant in the IRR and visible spectral regions (ICNIRP, 2004; ICNIRP, 2013).

Photobiological reactions can be classified in two types: **Primary reactions**, which derive from the interaction between photons and the chromophores/photoreceptors, observed in the first seconds or minutes after the irradiation of light and **secondary reactions**, as response to primary reactions, in hours or even days after the irradiation occurs (Karu *et al.*, 2003). The light absorption depending on the wavelength and causes primary reactions on the mitochondria. These are followed by a cascade of secondary reactions (photosignal transduction and amplification) in the cytoplasm, membrane and nucleus (Karu *et al.*, 1987).

Light of a specific wavelength excites electrons in cellular molecules, leading to the breaking or reorganization of chemical bonds therein. In this way specific biochemical reactions as well as whole cellular metabolism can be altered. The generation of singlet oxygen ($^1O_2$), and other highly-reactive free radicals (hydroxyl (HO•), anion superoxide ($O_2^{-\bullet}$), peroxide (ROO•) and hydroperoxyide (ROOH), enables the attack of the surrounding cellular molecules: proteins or deoxyribonucleic acid (DNA). They can interact with DNA causing some structural reorganization, and with other cellular targets such as retinal photoreceptors to cause deterioration of cellular function and cell death. Photochemical processes are in general dose dependent, meaning that low-level, long-term exposure gives rise to the same effect as short, lower radiance exposures (Pattison *et al.,* 2012*).* Depending on wavelength, different damage to DNA may occur, some of which may induce a disruption in the DNA strand, a structural reorganization, and/or deterioration of cellular function and possibly cell death (Zastrow *et al*., 2009).

The chromophores, after light absorption in a specific wavelengths range, induce oxidative damage to various cell compartments and functions. As most biologically relevant molecules are in a singlet state (figure 13) in their ground state (S_0), their photoactivation leads to an electronically excited singlet state ($^1S^*$). The photoexcitation may be followed by an intersystem crossing (ISC) and formation of an excited triplet state ($^3S^*$), which is able to transfer an electron (or hydrogen) to/from another molecule leading to a formation of a radical pair (**Type I of photosensitized damage**). The energy can be transferred to another molecule, which could become chemically reactive (e.g. radicals and reactive oxygen species) (Foote, 1976).

Interaction of an excited triplet state with molecular oxygen (which is in a triplet state in its ground state) may lead to an energy transfer (**Type II of photosensitized damage**). As a result, the photoexcited molecule returns to its ground state, while oxygen is activated to an excited singlet state, called singlet oxygen ($^1O_2$). Chromophores which upon photoexcitation undergo intersystem crossing and produce free radicals and singlet oxygen are known as photosensitizers (PS) (Nouri, 2011).

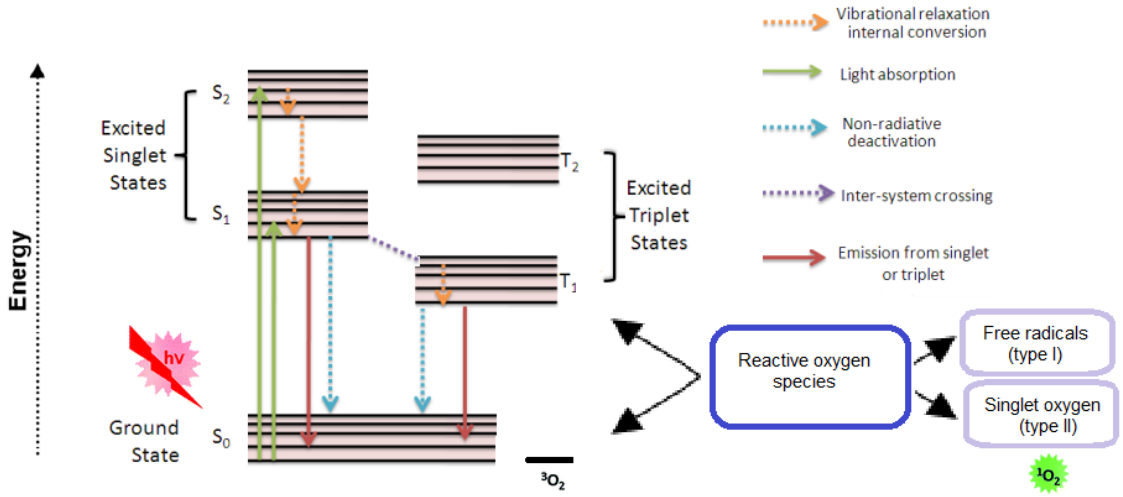

Fig. 13: The Jablonski diagram and the photochemical generation of ROS

ANNEX III Structure of the skin, Fitzpatrick skin type and optical radiation effects on skin

Structure of the skin

The epidermis (figure 14) is the most superficial layer of the skin. Its thickness varies from 50 µm (eye lids) to 1.5 mm (sole of the foot). The epidermis is almost exclusively constituted from a single cell type, the keratinocytes, organized in four cell layers. The basal layer is made from a single layer of actively dividing keratinocytes, adherent to a basal membrane, and containing small keratin filaments. Interspersed within basal keratinocytes are melanocytes (1 to 5%, depending on anatomical location) that produce pigments (melanin) in specific organelles (melanosomes) and emit dendrites through the upper keratinocytes layers. Basal keratinocytes progressively differentiate and migrate to form the upper epidermis layers. Stratum spinosum are made from 5 to 15 layers of large polygonal keratinocytes, and contain some Langerhans cells (dendritic cells, involved in antigen processing). Stratum granulosum is made from 1 to 4 layers of keratinocytes; these cells become flattened, their nuclei begin to degenerate, and they contain granules of keratin precursor (keratohyalin). The most external layer of the epidermis, stratum corneum, is made from 10 to 30 layers of dead keratinocytes (corneocytes) entirely filled with keratin fibrils.

The dermis is a conjunctive tissue, of approximately 1 mm thickness. The upper part of the dermis, papillary dermis, is in contact with the epidermis basal membrane, and forms papillae that increase contact surfaces with the epidermis (rete ridges). It is highly vascularised and contains neurofibrils and sensory receptors (Pacini corpuscles). The most important part of the dermis, reticular dermis, is made from intercrossed protein networks (collagen and elastin) produced by fibroblast cells, and is vascularised in its upper part. Dermis also contains skin annexes: sweat glands, simple tubulous glands of which the extremities form glomeruli deep into the dermis or even in the sub-cutaneous tissue (their mean density is 200 glands/cm^2, but may reach up to 600 glands/cm^2 in the forehead or in the palms), and hair follicles (actually an invagination of the epidermis) and their erector muscle and their associated oil gland (sebaceous gland).

Sub-cutaneous tissue is essentially made from fat and is vascularised.

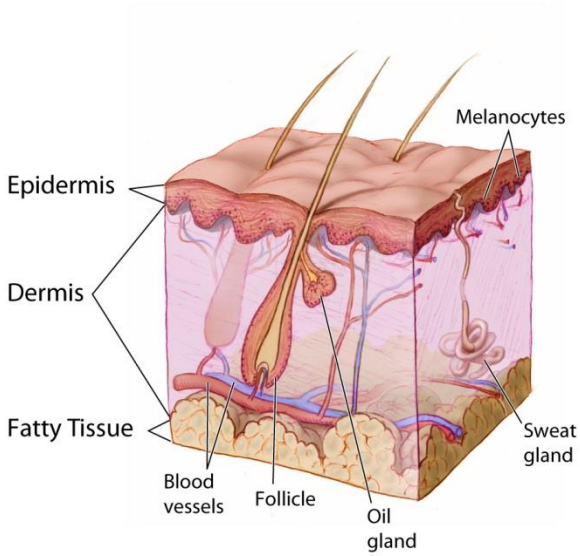

Fig. 14: Skin and its layers
(source: https://commons.wikimedia.org/wiki/File:Anatomy_The_Skin_-_NCI_Visuals_Online.jpg)

Fitzpatrick skin type classification

Skin type classification has been developed to characterize skin susceptibility to solar ultraviolet radiation.

Skin phototypes have been defined by Fitzpatrick according to the answers of white-skinned volunteers exposed to 3 MEDs (approximately equivalent to 45-60 minutes of noon exposure in the northern (20° to 45°) latitudes in the early summer) to two simple questions: "How painful is your sunburn (i.e. intensity of erythema, oedema and discomfort) after 24 hours?", and "How much tan will you develop in a week?".

Originally, the Fitzpatrick classification comprised four skin phototypes. Skin Phototype I: those who burn easily and do not tan at all; Skin Phototype II: those who burn easily and tan with difficulty (freckled and often red-haired individuals); Skin Phototype III: those who burn moderately, show immediate pigment darkening reactions and tan moderately; and Skin Phototype IV: those who do not burn and develop a good tan. Later, in addition to white-skinned persons, brown-skinned (Skin Phototype V: who seldom burn and always tan) and black-skinned (Skin Phototype VI: who never burn) persons were included in the classification (Fitzpatrick, 1988) – see Table 4.

Skin phototypes are independent of hair and eye colour, e.g., although persons with skin phototype I or II, with a very pale or pale complexion, usually have blond or red hairs and clear eyes, but they may have dark hair or eyes.

Table 4. Skin Phototypes (Fitzpatrick, 1988)

Phototype	Skin reaction to sun exposure	Skin colour	Hair colour	Eye colour
I	Always burns, never tans	Pale, Fair	Blond	Clear
II	Usually burns, sometimes tans	Fair, Freckles	Blond, Red	Clear
III	May burn, usually tans	Light Brown	Dark Blond, Light Brown	Hazel, Brown
IV	Rarely burns, always tans	Olive brown	Light Brown, Brown, Black	Dark
V	Seldom burns, always tans	Brown Moderate constitutional pigmentation	Dark Brown, Black	Dark
VI	Never burns	Black Marked constitutional pigmentation	Black	Dark

Optical radiation effects on skin

There are no sharp lines in wavelength-dependent biological effects in the skin. Thus, effects commonly known to be induced by e.g. UV-A radiation such as the DNA base damage, 7,8-dihydro-8-oxoguanine can be induced also by wavelengths of the visible spectrum (Kvam, 1997). Another example is the induction of bulky DNA adducts such as cyclobutane pyrimidine dimers by UV-B irradiation (Lehmann, 1995), which have been shown also to be induced by UV-A in rodent cells (Rochette, 2003).

Benign effects of optical radiation on healthy skin

Mild heating and erythema may occur below certain temperatures and irradiances below about 100 mW/cm^2 (British Standard, 2013). Sub-acute UV damage may cause loss of collagen in the dermis, termed photoaging. The action spectrum for photoaging is not well defined, but the wavelength range from UV to IR-A is suggested. There is no known threshold dose. Beneficial effects of low doses of UV exposure are pigment development through melanin production and skin hardening, both of which contribute to UV protection upon further UV exposure, as well as synthesis of vitamin D (UV-B-induced).

Vitamin D

Vitamin D (a steroid hormone) is essential for human health. It is essential for bone growth and for maintaining bone strength. In addition, vitamin D plays a role in cell growth: the function of many genes is modulated by vitamin D metabolites, and many cells have vitamin D receptors.

Synthesis of pre-vitamin D3 occurs in the skin from the conversion of 7-dehydrocholesterol from the keratinocytes cell membranes by UV radiation in the UV-B range (the action spectrum of vitamin D induction by UV exposure peaks at 297 nm). A thermochemical reaction leads to the formation of vitamin D3 (cholecalciferol). Vitamin D3 is transported to the liver and converted into its stored form, 25-hydroxyvitamin D [25(OH)D] (calcidiol), and further converted into its active form, 1,25- dihydroxyvitamin D [1,25(OH)2D] (calcitriol) in the kidneys. [It should be noted that keratinocytes are unique in being able to synthetize 1,25(OH)2D, expressing the vitamin D receptor, and responding to the 1,25(OH)2D generated (Bikle, 2012)]. Exposure of 600 cm^2 of the skin (i.e. the surface of face and back of hands) only needs 1/3 MED (300 J/m^2 for skin type III) to synthetize 400 IU (10 µg) vitamin D (Miyauchi and Nakajima, 2016).

Narrow-band (full width, half maximum 10-30 nm) UV irradiation with LEDs can increase the endogenous production of vitamin D. UV-B and UV-C irradiation with an LED device effectively increases serum levels of 25(OH)D in Vitamin D-starved mice irradiated twice a week for 4 weeks at 1 kJ/m^2 – suberythemal – at wavelengths between 268 and 316 nm (Morita *et al*., 2016). Barnkob *et al*. (2016) used UV LEDs in the wavelength range 280–340 nm to investigate optimal vitamin D bio-fortification in isolated pig skin fragments. A wavelength of 296 nm was found to be optimal for vitamin D3 production. The maximum dose of 20 kJ/m^2 produced 3.5–4 µg vitamin D3/cm^2 pig skin.

Malignant effects of optical radiation on healthy skin

Photothermal

Thermal pain is induced by skin temperatures greater than about 45°C (ICNIRP, 2013) (corresponding to about 100 mW/cm^2 (British Standard, 2013)). At this temperature and irradiance levels reversible or irreversible damage to skin structures can occur. The damage is accompanied by an inflammatory reaction in the skin. Normally, the aversion response limits exposure durations. However, in anaesthetised persons the aversion response may be compromised. This situation is unlikely to be relevant for exposure from non-medical devices. On the other hand, during occupational exposure workers may be prone to exceed the thermal limits. A skin condition caused by regular localised heating of the skin resulting in a reddish-brown colour, called erythema ab igne, may

indicate thermal damage of the skin. The presence of such erythemal damage may increase the risk of skin cancer development in the presence of carcinogenic chemicals or UV radiation exposure. The threshold doses to induce erythema ab igne may be below the thresholds of thermal pain (ICNIRP, 2013). If saunas and warming cabinets are equipped with IR-LEDs, these devices may cause erythema below the pain limit.

Photochemical

Sunburn, erythema and cancers

UV-B and UV-A exposure can induce delayed and immediate sunburn reactions (erythema), respectively, accompanied by inflammatory reactions. The erythemal action spectrum is defined in a standard by the Commission International de l'Eclairage (CIE 1998; ISO / CIE 1999).

Melanoma and non-melanoma skin cancers are the most common types of cancer in the Caucasian population. The very common actinic keratosis (AK) (pre-cancer) can be induced by cumulative solar and artificial UV radiation, as well as by exposure to polycyclic aromatic hydrocarbons. Precise prevalence and incidence figures are often unavailable as the lesions are not commonly reported to cancer registries. AK occurs mostly in skin types I-II (see Table 5). In a Dutch study at least one AK lesion was found in 38% of all subjects investigated above 50 years of age (Flohil *et al*., 2013). AK is the most common precursor of squamous cell carcinoma (SCC) in Caucasians (DermIS). Basal cell carcinoma (BCC) is induced by UV radiation, chemical carcinogens (e.g. arsenic), immunosuppression and genetic disorders, such as some of the photodermatoses (see Annex III, Photodermatoses). BCC is the most common skin tumour in humans and it seldom metastasises. Seventy-five percent of carcinomas occur in patients over 40 years of age. Cancer registries often exclude non-melanoma skin cancers. In South Wales, United Kingdom, the age-standardised incidence rates per 100 000 population in 1998 were 127.9 for men and 104.8 for women (Holme *et al*., 2000 in DermIS). Corresponding Danish numbers (per 100,000 person-years) for men and women in 2007 were 91.2 and 96.6, respectively (SCENIHR, 2012). The association between severe sunburns and basal cell carcinomas is likely (SCENIHR 2012), but the pathogenetic pathways of UV-B and UV-A radiation for basal cell carcinomas development need to be clarified (Calzavara-Pinton, 2015). Pathogenetic factors for squamous cell carcinoma (SCC) tumours (metastasising) are UV radiation, chronic inflammatory skin changes, chemical carcinogens, immunosuppression, as well as viral infections. In South Wales, United Kingdom, the age-standardised incidence rates per 100,000 population in 1998 were 25.2 for men and 8.6 for women (Holme *et al*., 2000). Corresponding Danish numbers (per 100,000 person-years) from 2007 were 19.1 and 12.0, respectively (SCENIHR 2012). Intermittent sun exposure and a history of sunburns, a predictor of intermittent exposure, increase the risk of cutaneous malignant melanoma (CMM) (SCENIHR 2012, Ghiasvand, 2016). The pathologic factors for this skin tumour are sun exposure (intermittent burning), artificial UV exposure, as well as phenotypic (fair skin) and genetic nature (in patients with e.g. xeroderma pigmentosum). CMM occurrence is increasing with ambient annual erythemal dose. It is the most frequent cause of death due to a skin disease. In Norway, where the age-standardised incidence rates are similar to those of Australia, the 2015-figures (per 100 000) were 41.2 for men and 36.5 for women (Cancer Registry of Norway, 2015). CMM incidence has increased faster than any other cancer in white populations during the past decades (Ghiasvand, 2016).

Immunosuppression

UV irradiation of the skin has an immunosuppressive effect. Both overexposure and sub-acute doses (<1 MED) can suppress adaptive cellular immunity (i.e. acquired immunity against a pathogenic agent or substance and effected by direct cell-to-cell contact). The immunosuppressive effects of UV radiation, in particular wavelengths shorter than about

320 nm, have been shown in several studies (reviewed by Schwartz, 2008). In animal studies such UV-induced suppression contributed to skin cancer formation and aggravation of bacterial/viral infections (Norval 2006b in SCENIHR, 2012). In humans, UV overexposure may cause flare-ups of herpes simplex viruses (Norval 2006a, Sayre *et al*., 2007, both in SCENIHR 2012). In humans, the suppressive effects of UV on skin immune status occur in the UV-B (around 300 nm) as well as in the UV-A (around 370 nm) range (Halliday *et al*., 2012).

One of the mechanisms is via the immunologically important lymphocytic cells: UV irradiation activates the regulatory T and B cells (Halliday *et al*., 2012). Urocanic acid, found predominantly in the stratum corneum of the epidermis, acts as an endogenous sunscreen by absorbing UV-B radiation. When exposed to UV-B irradiation, trans-urocanic acid is converted to the cis isomer which activates regulatory T cells and suppresses induction of immunity in human skin (Dahl *et al*, 2010).

UV exposure also has the ability to enhance the innate immune response (inborn defence against infectious agents). UV exposure increases levels of anti-bacterial proteins in the skin (Gläser *et al*., 2009 in SCENIHR, 2012) which may explain why solar exposure does not favour bacterial infections in general (Liu *et al*., 2006, SCENIHR, 2015).

Non-melanoma skin cancers and exposure to UV nail light

Nail curers uses UV-A radiation to dry (polymerize) nail polish and/or set acrylic nails. UV-A radiation is provided by small devices, rather inexpensive (from ca. 30 to 100 €), that can be used either in professional nail care salons or at home. For decades these devices have been fitted with compact fluorescent lamps emitting broad band UV-A (320 to 400 nm) and of a typical power of 36 W. More recently, UV LEDs have been introduced, that emit a narrower UV spectrum (375 to 420 nm), and of a typical power of 14 W.

Concern about the safety of this procedure was triggered by MacFarlane and Alonso (2009), who reported the occurrence of non-melanoma skin cancers on the hands after UV nail light exposure in two women. The first patient was a 55-year-old white woman with no specific risk factors (little recreational UV exposure, no solar damage, and no preceding human papillomavirus infection) who developed a squamous cell carcinoma in situ on the dorsal aspect of her right index finger and had a 15-year history of twice-monthly UV nail light exposure. The other patient was a 48-year-old white woman who developed a squamous cell carcinoma on the dorsum of her right hand. This patient, with moderate recreational UV exposure and no personal or family history of skin cancer, had a Fitzpatrick skin type III, with several actinic keratoses on her face and arms. There was no preceding human papillomavirus infection at this site or elsewhere. Questioning revealed previous exposure to UV nail lights approximately 8 times in 1 year, several years before her first skin cancer.

To evaluate the actual risk of skin cancer associated with exposure to UV-A lamps used in cosmetic nail treatment, Diffey (2012) constructed a mathematical model that combined age and UV exposure to compare the risk of developing SCC due to typical sun exposure with the risk of inducing these cancers from exposure to UV-A nail lamps. Calculations were based upon actual measurements of UV irradiance of a typical 18 watts device, giving an erythemally weighted output of 1.58 SED h^{-1} [Standard Erythema Dose, a measure of erythemal UV radiation exposure dose], and upon the assumption of a session every 3 weeks, i.e. an annual exposure dose of 3.8 SED [this dose can be compared to an estimation of a median baseline sun exposure level of 166 SED year + 85.5 SED per year holiday (SCHEER, 2016)]. Results were expressed as number needed to harm (NNH) and indicate that the risk of inducing an SCC from exposure to UV-A nail lamps is very low for a typical usage, since tens or hundreds of thousands of women would need to use a UV-A nail lamp regularly for one to go on to develop SCC on the dorsum of the hands as a direct consequence. Moreover, this risk can even be reduced to virtually zero by wearing fingerless gloves when the hands are being exposed.

Risk calculations by Diffey were based on measured irradiance of a single device fitted with fluorescent lamps of relatively small power. Markova and Weinstock (2013) measured the spectral irradiance of three common UV Nail Lamp devices: two fitted with broadband UV-A fluorescent bulbs (respectively 36 W with a peak emission at 368 nm, and 9 W with a peak emission at 370 nm), and one fitted with UV LEDs (405 nm, 6 W). They then used the action spectrum for human photocarcinogenesis (de Gruijl and Van der Leun, 1994) to determine the carcinogenic-effective irradiance of a 10 min UV nail lamp session and compare it with that of a single narrowband UV-B phototherapy course, a commonly used dermatological treatment, viewed as low risk for the development of nonmelanoma skin cancer. They calculated that over 13,000 fluorescent lamp and more than 40,000 UV-A LED sessions would be required to equal at the nail plane the UV dose received during one narrowband UV-B course, which represents over 250 years of weekly UV nail sessions to experience the same risk exposure.

Following a request from the Nail Manufacturers Council on Safety (an organization formed by the nonprofit trade association the Professional Beauty Association), Dowdy and Sayre (2013) conducted a photobiological safety evaluation of six nail curing lamps. Radiant hazards were assessed as defined in ANSI/IESNA RP-27 Recommended Practice for Photobiological Safety. Three of the devices evaluated were fluorescent UV nail lamps systems incorporating 2, 3 or 4 small 9 W lamps. The other three devices were LED-based incorporating arrays of 6 or 32 LEDs or 1 LED (single finger unit). Lamps were evaluated at three positions, 1 cm above the inner surface (approximating exposure to the hand) and the 20 cm RP-27 non-general light source distance, oriented 0° and 45° to the opening. At 1 cm distance, weighted Actinic UV ranged 1.2–1.7 μW cm^{-2}, classifying these devices into RP-27 Risk Group 1 (Low - for the finger unit) or 2 (Moderate); which corresponds to 29.8–276.25 min permissible daily exposure [the RP-27 risk group classification is based on an occupational exposure assumption]. At 20 cm on centre and 45°, actinic UV ranged 0.001–0.078 μW cm^{-2} and unweighted near UV (320–400 nm) ranged 0.001–0.483 mW cm^{-2}, and UV risk to skin and eyes were all within the Exempt classification. Likewise the retinal photochemical blue light hazard and retinal thermal and cornea/lens IR were also Exempt. According to this evaluation, the total exposure incurred during a typical nail lamp session represents a small fraction of the RP-27 permissible daily occupational exposure.

Shipp *et al.* (2014) measured the unweighted UV-A irradiance of 17 nail polish drying devices (in 16 salons), and evaluated the potential risk to the user by comparison with an energy density of UV-A shown to induce DNA damage (60 J cm^{-2}). The median UV-A exposure for a single visit was low (5.1 J cm^{-2}). These data suggest that the risk for carcinogenesis remain small. [It should be noted that the devices measured by Shippp *et al.* appear to have been fitted with fluorescent lamps].

In a research letter, Curtis *et al.*(2013) evaluated two nail curing lamps – not LEDs - and found that total MED (Minimum Erythema Dose) per session was 0.1 MED or less, representing annual doses of 1.1 to 1.5 MED, and raised the possibility that long-term exposure to UV nail lamps may have the potential to increase both cancer risk and photoaging.

Thus, regardless the metrics chosen, UV nail lamps and/or LEDs do not appear to significantly increase the lifetime risk of non melanoma skin cancer. However, data are lacking regarding the possibility of premature skin ageing, and the risk to the eyes of the professional operators should be considered.

Optical radiation effects in pathological conditions

Photodermatoses

It is reasonable to believe that patients diagnosed with a known photosensitivity disorder will avoid the radiation responsible for their symptoms. However, UV exposure may both relieve and aggravate symptoms in patients with conditions such as acne, psoriasis and atopic dermatitis. Also some viral infections, such as herpes simplex virus, can sometimes be exacerbated by UV. Individuals who experience intermittent or infrequent outbreaks of their condition may not avoid UV exposure at all times. Many lupus erythematosus patients may not be aware of their photosensitivity (SCENIHR, 2012) and therefore, will not always avoid UV exposure. Indoor lighting-triggered disease activity has been reported previously (SCENIHR, 2012).

The SCENIHR opinion on artificial light (2012) provides a comprehensive, yet not exhaustive list of various photodermatoses. Below, only a few of the most commonly occurring diseases/conditions are mentioned. A majority of both optical radiation-induced and -aggravated photodermatoses listed in the previous Opinion (SCENIHR, 2012) manifest with possible or established ocular involvement (Rambhatla *et al*., 2015)

A. Diseases induced by optical radiation

The wavelength dependency of some optical radiation-induced photodermatoses is presented in Table 6. The prevalence figures presented below for the various diseases were found at http://www.orpha.net/ if not specified otherwise.

1. Idiopathic or immune-based

Actinic prurigo can have childhood onset or onset before 20 years of age. The prevalence varies from 0.003% in Scotland to 8% in Chimila Indians of Colombia (Valbuena *et al*., 2014). Chronic actinic dermatitis (CAD) is an uncommon dermatitis thought to be a delayed-type hypersensitivity response against photo-induced cutaneous antigens, similar to allergic contact dermatitis (Rambhatla *et al*., 2015). CAD has adult onset. Prevalence is estimated to 1-5 in 10 000. Hydroa vacciniforme is a rare photodermatosis with childhood onset (Rambhatla *et al*., 2015). Indicated prevalence is 1-9 in 1 000 000. Lupus erythematosus can have various sub-types (see SCENIHR, 2012). They can have childhood onset and affect all age groups. Systemic lupus erythematosus (SLE) has prevalence in Europe of 12.5-39 per 100 000 (SCENIHR, 2012) while autosomal recessive SLE has a prevalence of <1 in 1 000 000. Polymorphic light eruption (PLE) can have childhood onset, but mean onset is in the second or third decade of life. PLE is the most common photodermatosis. In European countries the prevalence is up to 20% (Gruber-Wackernagel *et al*., 2014). PLE affects mostly women, and a prevalence of 33.4% in females of skin type I was reported by Rhodes *et al*. (2010) in Europe. Solar urticaria is an uncommon condition that affects all ages, but with a peak during the fourth and fifth decades of life (Rambhatla *et al*., 2015). Prevalence numbers are stated as 36 per 100 000 (orpah.net, 2016).

2. Genophotodermatoses

The diverse group of inherited photosensitive diseases is rare, and the diseases present with various wavelength susceptibility (SCENIHR, 2012). Xeroderma pigmentosum (XP) is characterised by defective DNA repair mechanism for UV damage associated with chromosome instability. XP has a prevalence of 1 in 1 000 000 in the USA and Europe, with higher figures in other countries and continents particularly in communities with a high degree of consanguinity (orpha.net, 2011). Birth prevalence is 0.23 per 100 000 in Europe (Orphanet Report Series, 2016).

3. Porphyrias

Porphyrias constitute a group of disorders related to enzymatic defects in the haem synthesis (Rimington, 1985). These result in increased synthesis of porphyrins and for some of the diseases, with possible cutaneous photosensitisation. The porphyrin absorption range is about 320-600 nm with the largest absorption maximum about 400 nm and smaller maxima between about 500-700 nm. Hepatocytes and bone marrow erythroblasts are the major cell types involved in haem synthesis and thus, enzymatic defects will be manifested in these cells (Rimington, 1985; Sassa, 2006). Six of the nine porphyrias described are associated with photosensitivity. Two of these are among the second and third most often occurring types. They can be of either erythropoietic or hepatic type or both (Sassa, 2006). The skin localisation of porphyrins of hepatic or erythrocyte origin is dependent on the water solubility of the porphyrins (Brun *et al*., 1991) and not necessarily the depth at which they accumulate. Thus, knowing the type of porphyria in a patient cannot indicate "safe" wavelengths within the porphyria absorption spectrum by choosing "appropriate" penetration depths. Porphyrias are, in general, rare diseases and prevalence and incidence vary between type of porphyria and countries (Table 6). As an example, erythropoietic protoporphyria (EPP), an autosomal recessive disease, has been described worldwide. The prevalence of EPP may vary based on the population allele frequency of the low-expression IVS3-48T>C allele, which ranges from approximately 1% in African Americans to approximately 43% in Japanese (Balwani *et al*., 2012).

Table 5: Prevalence and incidence of photosensitive porphyrias.
Total incidence of all porphyrias in Denmark is 0.52 in 100000 per year 1989-2013 (Christiansen *et al.*, 2016) [a)] Most common porphyria in children, third most common of all porphyrias. [b)]Holme *et al.*, 2006

Porphyria	Prevalence per million inhabitants (95% CI) if not otherwise stated	Geographic location	Reference	Prevalence, per million inhabitants Ref : orpha.net (year)	Incidence per million inhabitants (95% CI) if not otherwise stated	Geographic location	Reference
Variegate porphyria	3.2 (2.4-4.0)	11 European countries	Elder *et al.*, 2013	1-9 (2009)	0.08 (0.06-0.10)	11 European countries	Elder *et al.*, 2013 (2007-2009)
	Low: 0.4 High: 10.4	Poland Switzerland			Low: 0.01 High: 0.26	PolandSwitzerland	
					9 (1989-2013)	Denmark	Christiansen *et al.*, 2016
Erythropoietic protoporphyria[a)]	9.2 (7.7-11.6	11 European countries	Elder *et al.*, 2013	1-9 (between 1/75000 in the Netherlands and 1/200000 in Wales[b)](2013))	1) 2-5 2) 0.12 (0.10-0.15)		1) Pagon *et al.*, 2014 2) Elder *et al.*, 2013 (2007-2009)
	Low: 1.5 High: 27.7	Poland Norway			Low: 0.03 High: 0.36	Poland/ Spain Norway	

					73 (13 per million) (1989-2013)	Denmark	Christiansen *et al.*, 2016
Porphyria cutanea tarda	1 per 10 000	Sweden, Norway	Rossmann-Ringdahl *et al.*, 2005; Mykletun *et al.*, 2014	1/25000 Western Europe (2009)	650 (1 per 10 000) (1989-2013)	Denmark	Christiansen *et al.*, 2016
Hereditary coproporhyria	1 per 100 000	Czech Republic	Martásek, 1998	1/1 mill (2009)	4 (1989-2013)	Denmark	Christiansen *et al.*, 2016
Congenital erythropoietic porphyria					1 (1989-2013)	Denmark	Christiansen *et al.*, 2016

1
2

4. Photosensitivity with exogenous origin

Photosensitivity can be induced by skin exposure to plant and vegetable compounds (phytophotodermatitis), drugs, chemicals and cosmetics, all in combination with optical radiation. The most common mechanism for photosensitivity induced by drugs is phototoxicity, while a less frequent mechanism is photoallergy. Photoallergic contact dermatitis is a delayed-type hypersensitivity reaction in susceptible individuals. Most of these drugs or chemicals cause reactions after UV-A exposure although some can cause sensitisation with UV-B radiation or visible light (SCENIHR, 2012). A list of drugs associated with photosensitivity is provided by Valbuena *et al*. (2014) and a list of drugs and other compounds absorbing in the 290-700 nm wavelength range exhibiting phototoxicity can be found in Kleinman *et al*. (2010).

Photosensitisers used in photodynamic therapy of various cancers can elicit reversible skin phototoxic responses upon subsequent exposure to visible radiation (SCENIHR, 2012), such as from artificial light sources including LEDs.

A. Photo-aggravated dermatoses

This is a large and diverse group of diseases which are not primarily caused by optical radiation, but which can be exacerbated by such radiation. Examples of diseases and conditions are listed in e.g. SCENIHR 2012 and Rambhatla *et al*. (2015). Mechanisms of disease and wavelength dependence are not always known.

B. Susceptible groups

Children in general and persons affected by photodermatoses are susceptible to excessive optical radiation exposure of their skin. Childhood onset can occur for e.g. actinic prurigo, hydroa vacciniforme, lupus erythematosus, polymorphic light eruption, solar urticaria and xeroderma pigmentosum. Photosensitivity occurs in children for (at least) the following porphyrias: erythropoietic protoporphyria, congenital erythropoietic porphyria and hepatoerythropoietic porphyria.

Table 6: Wavelength dependency in photodermatoses (amended from Table 5 in SCENIHR Opinion: Health effects of artificial light, 2012. *Established or possible ocular involvement (Rambhatla *et al.*, 2015)

Classification		Wavelengths (nm)			
	Photodermatosis	UV-B (280-315)	UV-A (315-400)	Visible blue (400-500)	Visible green-red (500-780)
"Light"-induced, endogenous	Actinic prurigo*				
	Chronic actinic dermatitis*			(seldom)	
	Hydroa vacciniforme*				
	Lupus erythematosus* (may also be photoaggravated)		(UV-A?)		
	Polymorphic light eruption				
	Porphyria				
	Solar urticaria*				(green light?)
	Xeroderma pigmentosum*				
"Light"-induced, exogenous	Drug-/chemical-induced*			(few)	
	Photoallergic contact dermatitis				

Conclusions on photodermatoses

Porphyrias are rare diseases. Prevalence and incidence figures vary substantially between type of porphyria and countries. The absorption spectrum of the porphyrins present in patients with photosensitive porphyrias overlaps the emission spectra of LED lighting sources. The SCHEER could not find evidence for increases in the incidence of porphyrias and photodermatoses since the publication of the Opinion on artificial light (SCENIR, 2012). Theoretically, the incidence of the chemical/drug-induced types of porphyrias and induction and aggravation of any of the photodermatoses may increase with increased light exposure in general. Although it seems possible to elicit certain visible light-induced photosensitivity disorders with LED lighting sources, it must be kept in mind that these diseases are rare.

ANNEX IV Photometry, Radiometry and Dosimetry

Photometry and Radiometry

Photometry is the science of the measurement of light, in terms of its perceived brightness to the human eye. It is distinct from radiometry, which is the science of measurement of radiant energy (including light) in terms of absolute power. Concepts such as radiance, irradiance, radiant power and radiant intensity used in radiometry can easily be defined via simple geometric relationships. While sharing these identical relationships, photometry also introduces detector response modelled after human visual characteristics.

Power (watts) is converted to luminous flux in lumens via the integral equation:

where $V(\lambda)$ is the photopic response function of the human eye in day light,

Φ_v = flux (lumens), P_e = Power, K = constant (683 lm/W for photopic). The unit of luminous flux is the lumen.

Dosimetry

The emissions from an LED source can be quantified in terms of radiant power (watts). This should not be confused with the electrical input power used historically to specify incandescent lamps. The radiant power is usually the total emission of the source and is most appropriate for sources that emit equally in all directions. If the source is directional then it is more appropriate to specify the radiant intensity (watts per steradian) and if the source is not a point source, radiance (watts per square metre [of emitter] per steradian). These quantities are radiometric quantities and are appropriate across the optical spectrum (for ultraviolet, visible and infrared emissions).

It may also be appropriate to specify a spectral quantity to show how the contributions to the above quantities vary with wavelength – the emission spectrum.

With the spectral information, it is possible to weight the emission for a range of factors to take into account human (or other) responses. The response of the eye to optical radiation at different wavelengths has been experimentally determined and weighting with the response function, particularly for high light levels, gives the photometric quantities. Luminous flux (lumen) is equivalent to radiant power, weighted at each wavelength with the luminous efficacy function and summed across all wavelengths. The equivalent quantities for radiant intensity and radiance are luminous intensity (lumen per steradian or candela) and luminance (lumen per metre squared per steradian or candela per metre squared), respectively.

All of these quantities are parameters associated with the actual source or a virtual source (due to the use of a diffuser or reflectors).

The optical radiation incident on a surface, which could be the eye or the skin, is quantified in terms of irradiance (watts per square metre). The equivalent photometric quantity is illuminance (lumen per square metre or lux). Since radiance is generally conserved in an optical system, the radiance on the retina will generally be the same as the radiance of the source.

Spectral data for the optical radiation incident on a surface, for example in watts per square metre per nanometre, can be used to weight for a range of hazard or beneficial effects. In this Opinion, reference is made to a number of studies, which suggest that the blue emission from LEDs may be of concern. The International Commission on Non-Ionizing Radiation Protection (ICNIRP, 2013) has published guidelines on limits for

exposure to blue light, which take into account the effectiveness of optical radiation to cause adverse effects at different wavelengths.

The spectral irradiance from an LED source is weighted at each wavelength and the resulting weighted spectrum is summed for comparison with the ICNIRP exposure limit. Since the weighting function peaks at about 440 nm, decreasing by a factor of ten for wavelengths less than 400 nm and greater than 500 nm, any incident blue radiation is more significant. This is shown in Fig. 15.

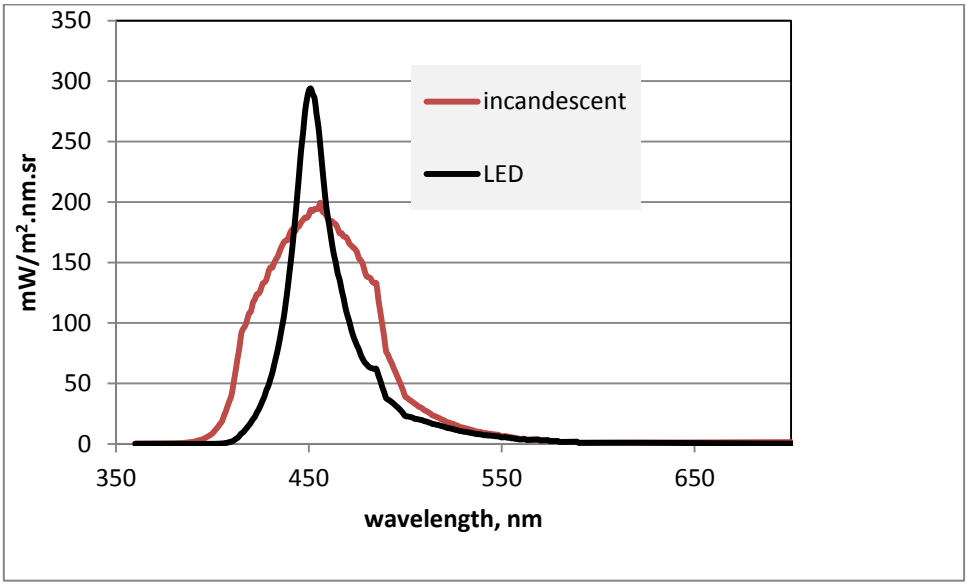

Fig. 15: Emission spectra from an LED and an incandescent lamp (in figure 3), weighted with the blue light action spectrum

Fig. 15 shows the weighted (for blue light hazard, Fig.7) spectral radiance of the incandescent lamp and LED lamp shown in Fig. 3. When the values were summed, the weighted radiance was 14 W m^{-2} sr^{-1} for the LED lamp and 10 W m^{-2} sr^{-1} for the incandescent lamp. The ICNIRP exposure limit for long-term exposure (> 10000 s or about 3 hours) is 100 W m^{-2} sr^{-1}.

Most lighting sources are not directly visible to observers in order to avoid a glare source. Sources may be shielded or fitted with diffusers. The exceptions are indicator devices and, for example, vehicle lighting, which is in the direct field of view, and illuminated screens. Therefore, the general exposure condition is to indirect optical radiation. ICNIRP provides a general rule for white light sources, which is that if the luminance is less than 10^4 cd m^{-2}, it is unlikely to be a hazard. Screens are usually up to about 4% of this luminance (O'Hagan *et al.* 2016).

ANNEX V Circadian rhythm

Generation of the circadian rhythm

The biological clocks consists of multiple 'clocks': 1) the central clock in the brain (the suprachiasmatic nucleus or SCN) and 2) peripheral clocks in almost all organs including heart, liver and kidneys. The peripheral clocks are regulated by the central clock (Dibner, Schibler *et al.* 2010). A self-sustaining molecular oscillator generates the circadian rhythms at a cellular level. This oscillator comprises genes and proteins that are organized in positive and negative transcription translation feedback loops (Takahashi, 2017). In short, the heterodimer transcription factor CLOCK/BMAL1 drives the transcription of the *Period* and *Cryptochrome* genes. The proteins translated from these transcripts gradually accumulate in the nucleus and shut down the expression of their own genes by repressing the transcription of the CLOCK/BMAL1 heterodimer. This process is influenced by post-translational modifications that affect the stability of the clock proteins and, thereby, influence the periodicity of circadian rhythms. In turn, this determines, for example, a person's chronotype (i.e. a morning or evening person) (Takahashi, 2017).

Function of circadian rhythms

Circadian rhythms most likely evolved to adapt and respond optimally to daily environmental cycles. It enables anticipation to expected events and ensures that bodily processes occur in a temporal and synchronized fashion at the most optimal timing related to the environment. A simplified example: eating when food is present and subsequently optimize metabolism processes after eating. The bodily processes regulated in a circadian fashion are widespread and linked. Ranging from behaviour (sleep/wake cycles), cognition (attention, concentration), the immune system and repair mechanisms, to numerous physiological processes including endocrine functioning, metabolism, cardiovascular functioning etc. It has been shown that circadian rhythms occur in 2-10% of a tissue's gene expression and, in addition, several post-transcriptional mechanisms result in circadian rhythms in protein expression (Takahashi 2017).

Measuring circadian rhythms in humans

To determine if circadian rhythms are influenced by external stimuli, several biomarkers for circadian rhythms are usually investigated. These include body temperature, melatonin and cortisol, of which melatonin is the most widespread used marker. Melatonin is one of the hormones with a robust circadian rhythm and its levels are easily assessed using saliva, serum or urine. The timing of melatonin production from the pineal gland is directly regulated by the central clock in the brain, the SCN. During night time, norepinephrine is released from sympathetic nerve endings to the pineal gland which regulates the key enzyme in melatonin production, arylalkylamine N-acetyltransferase (AANAT) (Schomerus and Korf 2005). Melatonin levels rise during the dark period and decrease at the end of the dark period. However, regulation of melatonin is not only via light/dark, since melatonin levels decrease towards the end of the night when no light is present and darkness during the day will not result in melatonin production. As such, melatonin levels are often used as a marker for a person's circadian phase, although this relation involves other aspects as well. Exposure to light at night reduces the production of melatonin, since norepinephrine levels drop (Schomerus and Korf 2005), but changes in circadian phase depend on other aspects as well (light during the day and other zeitgebers, such as food). Melatonin also rises at night in nocturnal animals, and, as such, it is better described as a hormone of the night, rather than a sleep hormone.

Consequences of disturbance of the circadian rhythm by light

As described in section 6.9.1 negative health effects of optical radiation from LEDs, specifically, have not been investigated. It is expected that these effects are not LED-specific; they apply to exposure to light during the evening that influences the circadian system in general. The effects may, however, be enhanced for LEDs compared to traditional light sources at similar illumination levels, due to the particular spectral emission pattern of certain types of LEDs. In addition, it is important to note that direct causal relations of the use of LEDs or other artificial light sources during the evening on health have not been investigated. Indications are obtained from association studies, circumstantial evidence and hypothesized effects based on studies investigating other types of circadian disturbance.

Disturbance of the circadian system has been associated with several negative health effects. This is mainly the case for relatively severe disturbances of the circadian system that, for example, occur due to shift work or jetlag. For example, circadian disturbance as might occur due to shift work has been associated with cancer, metabolic health effects, and cognitive functioning (IARC 2010, Wang, Armstrong *et al.* 2011, ANSES 2016, Mattis and Sehgal 2016). Although the circadian disturbance observed due to evening light exposure is less severe, some underlying mechanisms and consequences might be similar.

An important consequence of the circadian disturbance due to light during the evening is its effect on sleep. As described in more detail above, the studies by Cajochen *et al.* and Chang *et al.* indicate that use of certain types of LEDs, similar to other artificial light sources, can result in reduced sleepiness (Cajochen, Frey *et al.* 2011, Chang, Aeschbach *et al.* 2014) and increased latency to sleep (Chang, Aeschbach *et al.* 2014), possibly causing shorter sleep duration and poorer sleep quality. It is important to note that, regardless of the cause (i.e. being artificial light or other factors), reduced sleep duration and quality is associated with poorer cognitive performance, fatigue, altered mood and increased health and safety risks (Christoffersson, Vagesjo *et al.* 2014, Engle-Friedman 2014, Burke, Scheer *et al.* 2015, Cedernaes, Schioth *et al.* 2015).

Furthermore, additional light during the evening has been hypothesized to phase delay circadian rhythms. Delay in the circadian rhythm can result in 'social jetlag'. This refers to the phenomenon that the circadian rhythm is delayed but the social environment requires behavioural patterns to remain at the earlier phase (Wittmann, Dinich *et al.* 2006). In other words, a person still has to get up early in the morning to go to work/school. This can cause several important bodily processes to occur 'out of sync' with the biological clock, such as food consumption. This desynchronization of external and internal stimuli might be underlying some of the health effects related to disturbances of the circadian system. Social jetlag has mainly been associated with risk factors for cardio-metabolic diseases (Parsons, Moffitt *et al.* 2015, Wong, Hasler *et al.* 2015). Furthermore, evening light exposure might enhance delayed sleep-wake phase disorder (DSWPD) in sensitive persons. This disorder is characterized by late sleep and wake times and poorer sleep quality (Joo, Abbott *et al.* 2017, Magee, Marbas *et al.* 2016).

In addition to observed effects of evening light on sleep in experimental settings, it has been suggested that evening exposure to light might have an direct effect on food consumption and metabolism (Versteeg, Stenvers *et al.* 2016). It has been hypothesized that evening light causes increased food consumption at unfavourable moments (i.e. when metabolism processes are in their rest phase). In addition, an association has been observed between melatonin levels and metabolic disorders. Melatonin might have a direct effect on food intake and melatonin receptors are also present on pancreatic cells. Polymorphisms in the melatonin receptor have been associated with increased risk of type 2 diabetes (Versteeg, Stenvers *et al.* 2016).

In summary, disturbances of the circadian rhythm can result in negative consequences on sleep, cognitive performance and, in the long term, on metabolic risk factors. Since no experimental studies have been performed with chronic exposure (multiple years) to artificial light during the evening, it is currently unknown if the disturbance of the circadian rhythm remains, increases or reduces after chronic exposure to light during the evening.

ANNEX VI Hazardous waste due to the materials used for producing Light-Emitting Diodes (LEDs)

A South Korean/U.S. investigation on the toxic potential of LEDs, CFLs and incandescent lamps, found that in comparing the bulbs on an equivalent quantity basis with respect to the expected lifetimes of the bulbs, the CFLs and LEDs have 3-26 and 2-3 times higher toxicity potential impacts than the incandescent bulb, respectively (Lim *et al.,* 2011). Arsenic is present as gallium arsenide is found in light emitting diodes (LEDs). The element is a human carcinogen and exposure to arsenic can result in various skin diseases and can decrease nerve conduction velocity[6]. Lead is a potent neurotoxin, and short-term exposure to high concentrations of lead can cause vomiting, diarrhoea, convulsions and damage to the kidney and reproductive system. It can also cause anaemia, increased blood pressure, and induce miscarriage for pregnant women. Children are considered to be particularly vulnerable to exposure to lead, for it can damage nervous connections and cause brain disorders[7].

Except for these heavy metals, TBBA (tetrabromobisphenol-A), PBB (polybrominated biphenyls) and PBDE (polybrominated diphenyl ethers) could be encountered as fire retardants for plastics (thermoplastic components, cable insulation). TBBA is presently the most widely used flame retardant in printed wiring boards and covers for components - brominated flame retardants (BFRs). The combustion of these halogenated compounds releases toxic emissions including dioxins which can cause reproductive and developmental problems, damage the immune system, interfere with hormones and also cause cancer[8].

Polyvinyl chloride (PVC) is mainly found in the plastic components of electrical and electronic equipment. When burned, PVC releases dioxins, furans and phthalates, some of which are known reproductive toxicants and carcinogens (Hazardous substances in e-wastes., 2009).[9]

Phthalates used as softeners to PVC can easily leach into the environment. Epidemiological data has suggested an association between indoor exposure to phtalates and asthmatic and allergic reactions in children (Bornehag *et al*., 2010)

[6] World Health Organization (WHO), Arsenic, Fact Sheet 372 (June 2016) http://www.who.int/mediacentre/factsheets/fs372/en/

[7] World Health Organization (WHO), Lead poisoning and health, Fact Sheet 379 (September 2016) http://www.who.int/mediacentre/factsheets/fs379/en/

[8] World Health Organization (WHO), Dioxins and their effects on human health, Fact Sheet 225 (October 2016) http://www.who.int/mediacentre/factsheets/fs225/en/

[9]Hazardous substances in e-wastes, (2009). Retrieved May 17, 2015 at http://ewasteguide.info/hazardous-substances.

ANNEX VII: Literature review

Comprehensive literature searching involved capturing the scientific literature about the LED effects on skin, eye, retina, macula, cornea, lens tear film, circadian rhythm, circadian disruption, melatonin suppression.

Search strategy and selection of publications

Example Topic: circadian effects (Search EC library and e-resources centre)

Selection on Title of the following topics: 19 references

Circadian rhythm: 8 out of 12

Blue light AND circadian AND human: 1 out of 9

Blue light AND circadian disruption: 4 out of 15

LED AND circadian rhythm: 2 out of 2

Melatonin suppression: 4 out of 16

Circadian light: 0 out of 3

Based on abstracts, 9 papers were excluded, since they were not relevant; 3 papers were excluded because either the full text was not available or they were not available in English; 7 publications were included in the present opinion.

References from RIVM report 2014: 13 references were selected from this report. The search strategy used in this report was also repeated to get an update on the literature since 2014. This resulted in 179 publications. Based on title, 7 publications were selected. Based on abstract 4 publications were excluded since they were not relevant. 3 publications were used in the Opinion. One of them had also been identified in the search of the EC library and e-resources centre.