ASSESSMENT OF BLUE LIGHT EXPOSURE IN THE OCCUPATIONAL VISUAL FIELD

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Abstract

Problem statement

Rapid technological advances are occurring in the lighting industry, with greater diffusion of cost-effective sources incorporating light emitting diode (LED) and metal halide lamps. These new lamps are often brighter than traditional lamps and are widely used in various applications from general homes to medical/industrial settings. They can have significantly different spectral radiant energy distributions, including shorter wavelengths.

Intense blue-rich lamps may represent a hazard, i.e. the so-called “blue light” hazard, and potentially contribute to age-related macular degeneration (AMD). The mechanism of retinal damage is believed to be associated with photochemical oxidation, leading to cumulative loss of photoreceptors. From a public health perspective, AMD is the major cause of low vision and blindness in older people aged 50 and over.

As blue light-related AMD, like noise-related hearing loss, can be progressive, there may not be any obvious symptoms. Given the increasingly wide distribution of blue-rich light sources there is a need to better understand blue light exposure, and how these exposures are linked to macular degeneration.

Gap analysis

The existing literature related to blue light exposure and potential health effects are scattered in multidisciplinary areas, such as medicine, physics, occupational hygiene, biology, chemistry, and nutrition. There is a shortage of literature from an occupational health perspective. Hence, there is a need to organise the evidence and interpret the literature for occupational health professionals, who advise management and workers on workplace hazards. It is also clear that exposure studies of workers using blue light sources are limited, potentially due to the complexity/cost of measurement. Exposure assessment is a complex task requiring detailed time/activity assessment relative to direct and reflected blue light in the visual field.

Purpose statement

This exploratory research has two aims. Firstly, it aims to gather evidence about blue light exposures and risks of retinal photochemical damage through reviewing available published literature. Secondly, it aims to conduct empirical case studies for selected work environments and tasks and compare measured values with current exposure guidelines.

General Research questions

1. How significant is blue light exposure in the Occupational Visual Field (OVF)?
   a. What evidence is there relating to occupational blue light hazards/exposures/controls? (Literature review)
   b. Is the exposure of selected workers in proximity to known blue light sources sufficient to exceed the current blue light exposure TLVs? (Case study approach)

Methodology

The methodology comprises comprise a narrative literature review and three empirical case studies.

Literature Review

The literature review was conducted in terms of an occupational hygiene paradigm (Hazard/Exposure/Control) with a systematic search strategy using PubMed, Scopus and Embase databases and hand-searching. The review covered the areas of the recognition of blue light hazards, measuring the exposure, and recommending how to control the exposure and hazards. The results of the search were tabulated and summarized to assess the quality of evidence. The yield was classified into 3 levels of quality (High, Medium, and Low). JBI and SYRCLE tools were used for the classification. The audience for the review is occupational health professionals, regulators and industrial unions.

Three Case studies in different workplaces with blue light sources

All case studies were approached in the same way. Firstly, field observations were conducted to understand; the workers' task, working processes, durations and estimated observation distances and average frequency of light exposure. Secondly, using the observational data, blue light exposure in a nail salon, video recording studio and dental simulation clinic using blue light sources were simulated and a comparison made with existing exposure guidelines.

- Case study 1 (Nail curing lamp)

Observations in seven nail salons in Adelaide were conducted to observe the tasks, work durations, types of light sources and other working conditions. Nail art videos on the internet were also watched to characterise the diversity of nail technicians' working processes. The information obtained from field observations in a series of salons was used in conjunction with a series of laboratory experiments that simulated exposure using two nail curing lamps.

- Case study 2 (Various light sources in a video recording studio)

Observational data in a video recording studio in the University of Adelaide were collected with the three most common lighting backgrounds (panel LEDs, spotlights and ceiling lamps). Three probable recording scenarios were created from the observations and each light source was directly measured in the user's OVFs using three scenarios in the studio.

- Case study 3 (dental curing lamp)

Observations in the dental simulation clinic in the University of Adelaide were conducted to understand simulation courses using a dental curing lamp, curing durations, types of light sources in the clinic and other students' working conditions. Assessments of a dental curing lamp were conducted in both the simulation clinic and in a laboratory.

A spectroradiometer (Specbos 1211UV) was used to measure the spectral radiances in the OVF. The data were compared to the exposure guidelines e.g. American Conference of Governmental Industrial Hygienists Threshold Limit Values (ACGIH TLV) and International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines.

Blue light hazard function (BLHF) illuminance

To measure BLHF illuminance and irradiance, a blue filter (HOYA B440) was used on a professional lux meter (as above) and with the mobile devices.

Blue light hazard function (BLHF) luminance

To measure BLHF luminance, a blue filter (HOYA B440) was used on a professional luminance meter (Minolta nt-1°).

Main Findings

Narrative literature review (OVF perspective)

Hazard - Blue light exposure can damage the visual photoreceptors and lead to degenerative retinal diseases. The damage from sources can be cumulative and irreversible. Workers who are exposed to very intense sources, such as arc welding lamps, can be more at risk of retinal damage than other workers. A wider group of workers with chronic exposures to sources such as blue rich LEDs may experience long term effects. Generally aging is closely related to retinal photochemical injuries. Younger eyes (less than 20 years old) exposed to blue light have been reported to have a 20 % increased risk for retinal photochemical damage compared to the eyes in people in their 60s. Therefore, it is possible that workers who are exposed to blue light sources for a long time may have the potential risk of retinal damage. AMD, one of the most common retinal diseases, mainly occurs in elderly populations. It can be caused by many potential risk factors and occupational long term blue light (380-550 nm) exposure could be one of those. It should be noted that new approaches for treating retinal damage, such as retinal stem cells or nutritional supplements, have been recently described.

Exposure - It is difficult to estimate the potential risk on eyes from blue light exposure. The OVF should be considered in the workplace due to eye/head movements, the actual task and worker's behaviour. ICNIRP guidelines consider the field of view from blue light exposure utilising a range of acceptance averaging angles depending on exposure duration. The blue light effective radiance (L_B) and the radiance dose (D_B) are defined as exposure parameters, and guidelines stem from animal studies and acute exposures.

Controls - The hazard control literature largely relates to personal protective equipment, selection and management of sources.

Case study 1 (nail curing lamp)

UV nail curing lamps which are designed for nail coating curing processes, emit UV radiation (UVR) and blue light. There are two types of UV nail lamps (UV fluorescent and LED lamps) and LED type curing lamps are the most common type of the lamps used currently. Two LED lamps were considered in lab simulation.

The highest peak emission of both LED nail lamps was at 404 nm. The stronger powered (36W) LED nail lamp showed higher radiances than the low powered (18W) lamp. The levels of radiance and radiance dose (L_Bs and D_Bs) were well below the current limits, even in the worst case exposure scenario. The design of UV nail lamp openings is such that they generally face the actual users and thus customers may have higher exposures than nail technicians during the brief curing process. However, most customers only visit nail salons periodically (e.g. monthly), while nail technicians have many customers to attend to daily. Hence, the duration of workers' exposure to UV nail lamps would greatly exceed that of a typical customer's exposure (e.g. Estimated viewing durations in worst case were 900 seconds for a customer and 2700 seconds for a nail technician.)

Interestingly, the corners of the 18W LED nail curing lamp showed higher values of L_Bs than at the centre. This indicates that the amount of exposure can differ depending on the position of the person. This research is the first to attempt to measure the spectral radiances and the spectral radiance doses in terms of the actual working environment.

Case study 2 (bright light sources in a video recording studio)

Several standard presentation options were available. Depending on the options selected different light sources are introduced (e.g. spotlight, vs soft lights and side lights). Generally, the lights in a video recording studio are brighter than in typical offices or industrial areas. Except for the spotlight option, all light sources in the studio were installed to the ceiling and toward the centre of the stage and did not face toward a presenter's eyes directly when the presenter looks to the front. However, the eyes and the head of a human being move continuously and a presenter/presenters can have diverse working positions during recording. Especially, when two presenters are sitting across from each other under front light sources, both people can be exposed to intense bright light sources. The radiance of spotlights exceeds 100 W/m^{2}sr and the contrast between the illuminated spot and dark background studio was very high and discomfort glare is indicated. Depending on the motion of a presenter, one or more front light sources (4 LED panels and 2 spotlight LEDs) were included in the OVF. Generally, blue weighted radiance levels did not exceed the limit, and radiance doses are not expected to be exceeded under normal usage.

Case study 3 (dental curing lamp)

A dental curing lamp emits blue light wavelengths ranging from 400 to 450 nm and is used for polymerizing dental resin-based materials. Dental students using a dental simulation suite were observed. Second year dental students receive their practical training in the dental simulation clinic for around 160 hours per one semester. The working distances were quite close from 15 to 30 cm and the average of angles from the teeth-treated to students' eyes was 45 degrees. However, both distances and angles varied depending on the locations of the treatment. The potential exposure duration of a typical- and the worst-case scenario estimated by the observations were 108 sec and 240 sec during 3-hour classes respectively.

The blue weighted radiance levels were highly variable depending on targets, angles and the locations of teeth, ranging from 2.5 to 212 W/m^{2}sr.

Novelty

This research is novel in terms of systematically assessing blue light exposure in the occupational visual field, both in terms of radiance and radiance dose.

The exposure to blue light sources was characterised by a combination of radiance measurement and time activity patterns through the data from actual field-work observations. Lastly, preliminary research into how low-cost photometry (illuminance and luminance) could be adapted for radiometry was undertaken.

Conclusions

Blue light exposures in the three case studies were generally low. However, exposure is highly directional. Intense blue rich sources in the occupational visual field may pose appreciable retinal risks. Blue light exposures with hand held sources are problematic.

With few empirical studies, multidisciplinary literature, and expensive instrumentation it appears that most occupational health professionals are unfamiliar with the blue light exposure assessment technology.

Recommendations

Based on the research conducted, several recommendations can be made for researchers, occupational health professionals and manufacturers.

<u>For researchers</u>

Systematic exposure assessment and epidemiological studies are needed. These will assist in formulating human-derived exposure standards.

For occupational health professionals

Occupational health professionals should understand light sources through lighting surveys in the workplace and should assess the blue light exposure in the OVF taking into account time activity patterns and directionality of lighting.

For manufacturers

More specific information related to classifications of their light sources and potential health effects from exposure should be provided for users.

The design of lighting systems may influence exposure. In terms of managing potential exposure in a nail salon context, a covered design is recommended.

A modified dental curing lamp with a separate annular light source could be developed for users wearing blue filtering glasses. This would assist in more precise curing, whilst also protecting the dentist.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

I give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository, the Library Search and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

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Signed: _______ ___

Date: _________30/06/2020_____________

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So Young Lee

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List of Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AIOH	Australian Institute of Occupational Hygienists
AMD	Age-related Macular Degeneration
ARM	Age-related maculopathy
AS/NZS	Standards Australia and Standards New Zealand
BLH	Blue Light Hazard
CCT	Correlated Colour Temperature
cd/m^2	Candela per square meter
CFL	Compact Fluorescent Light bulb
CIE	International Commission on Illumination
ELV	Exposure Limit Value
GLS	General Light Service
ICNIRP	International Commission on Non-ionizing Radiation Protection
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells
JBI	Joanna Briggs Institute
LED	Light Emitting Diode
MD	Macular Degeneration
MPE	Maximum Permissible Exposure
mrad	Milliradian
nm	Nanometer
OS	Oxidative Stress
OVF	Occupational Visual Field
PPE	Personal Protective Equipment
RG	Risk Group
ROS	Reactive Oxygen Species
RPE	Retinal Pigment Epithelium
SCENIHR	Scientific Committee on Emerging and Newly Identified Health Risks
SYRCLE	Systematic Review Centre for Laboratory Animal Experimentation
TLVs	Threshold Limit Values
W/m^2sr	Watt per square meter steradian
γ_{ph}	Acceptance averaging angle
µsec	Microsecond

Thesis Overview

The thesis comprises three main elements: Narrative literature review (Chapter 2), three empirical case studies (Chapters 4 to 6) and discussion, conclusions, and recommendations (Chapters 7 to 8).

Exposure to blue light is reviewed in Chapter 2 (Narrative literature review) and organised in terms of a Hazard/Exposure/Control framework.

Based on the evidence from the narrative literature review, there are three empirical case studies (Chapters 4 to 6) with regard to exposure scenarios (typical/worst case scenarios) using field observations and simulation experiments.

The main findings from the literature review and the case studies are discussed in Chapter 7 using "Work/Worker/Workplace" risk factors, and also including an assessment of the novelty, strengths and limitations of the research.

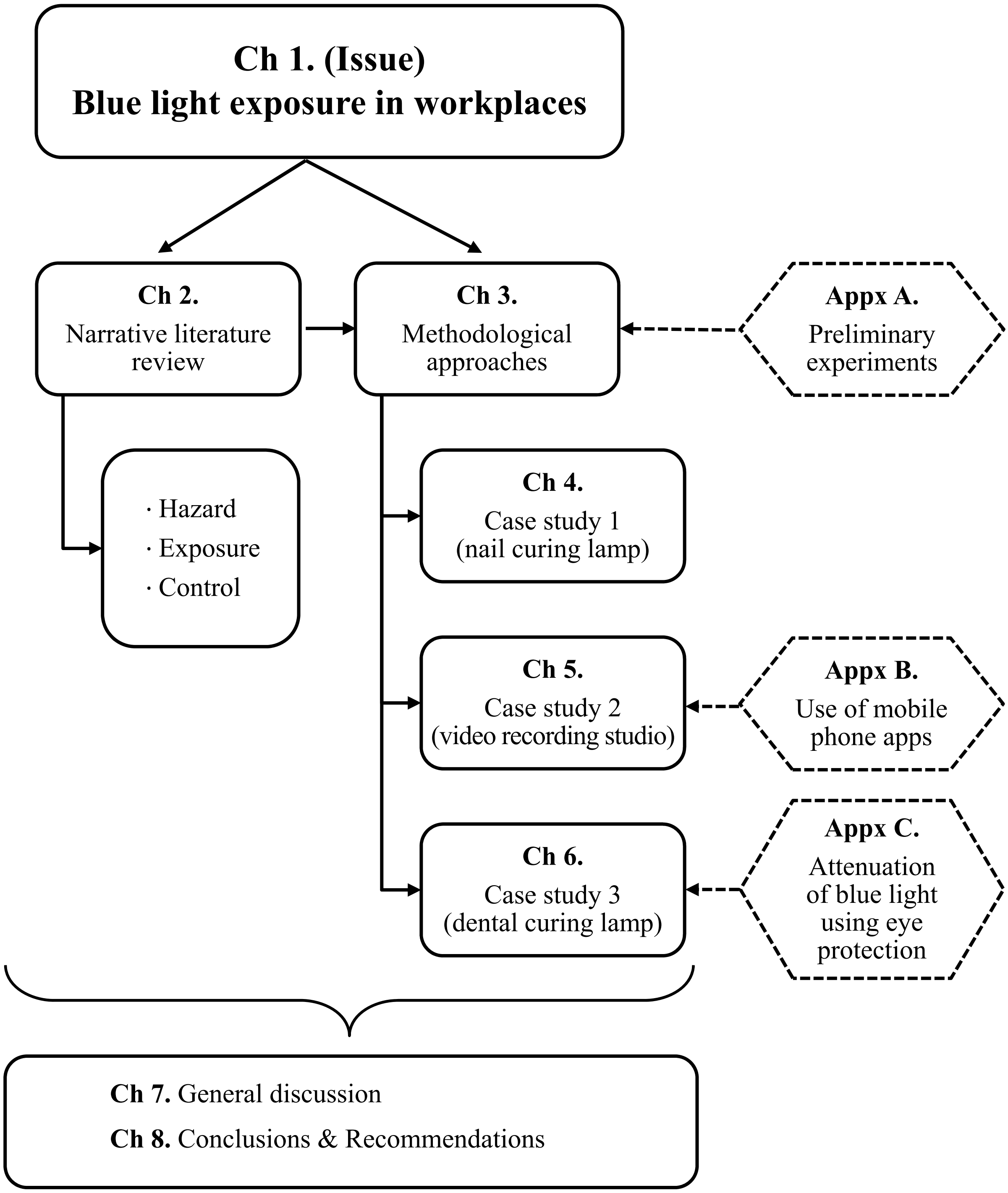
Substantive conclusions based on the results from all studies and practical recommendations for stakeholders are described in Chapter 8.

Preliminary investigations, low cost methods development and ancillary studies are described in the appendices.

In Appendix A, preliminary experiments were conducted to assess general light sources, utilising a spectroradiometer and a luminance meter fitted with a blue filter. Appendix B considered ways of undertaking low cost lighting surveys: Mobile phone applications (light meter apps and Google Street View) were explored. In Appendix C, the filtering ability of certain eye protective glasses was examined using blue light sources used in Case studies 1 and 3.

The overall thesis outline is illustrated in the following figure and fundamental contents of each chapter are briefly summarised in the overview table.

Structural overview of the thesis



THESIS OVERVIEW TABLE

Chapter	Core of chapter	Key points
Chapter 1. General Introduction	• Potential exposure to blue light • General information for assessing blue light sources	Blue light is emitted from a variety of light sources and can cause many effects e.g. circadian rhythm alteration, psychological effects and photoreceptor damage. Some workers who use or are exposed to blue light sources may be at higher risk of health effects. However, due to lack of epidemiological studies or clinical trials about this, assessment for identifying risk of exposure to blue light in the workplace is not properly understood. Most occupational health professionals are also unfamiliar with blue light assessment. So far, guidelines associated with the blue-light photochemical retinal hazard from ICNIRP and ACGIH are available to evaluate occupational exposure to blue light. This chapter emphasises the concept of the Occupational Visual Field (OVF) in assessing blue light exposure in the workplace.
Chapter 2. Narrative literature review	• A narrative literature review was conducted to classify the evidence of the blue light hazard from exposure to blue light.	**Hazard:** Blue light may affect eyes, skin and influence circadian rhythms. Photochemical damage to the retina, in particular, is thought to be irreversible and accumulates depending on exposure /duration/intensity. Age-related macular degeneration (AMD), the most common cause of blindness or vision impairment, may potentially be caused by retinal damage from blue light exposure. **Exposure:** Exposure assessment of blue light sources can be measured using blue weighted spectral radiance (L_B) and radiance dose (D_B) provided

	• The search strategy utilised three bibliographic databases (PubMed, Scopus and Embase), hand-searching and backward searching. The yield was thematically organised in a Hazard-Exposure-Control framework.	by ICNIRP guidelines and ACGIH TLVs and the values of L_B and D_B need to be considered in the occupational visual field (OVF). However, very few studies of blue light exposure have been published **Control:** Other than avoidance or source control, the amount of exposure to blue light can be reduced and managed by personal protective equipment (PPE), such as blue filtering glasses or blue blocking intraocular lens (IOL). Certain nutritional supplements such as lutein or zeaxanthin, can prevent the damage. There are also several treatment methods (e.g. laser and drug treatment) and new attempts (e.g. gene therapy or stem-cell therapy) for AMD.
Chapter 3. Methodological approaches for case studies	• Methodology for three case studies (Chapters 4 to 6) and an introduction of additional experiments (Appendices A to C)	A case study approach was used to investigate blue light exposure. A common methodology was used; Field observations, definition of exposure scenarios and exposure assessments utilising simulation experiments. Potential exposures were evaluated by using a spectroradiometer and levels of L_{BS} and D_{BS} were measured considering different directions and intensities.

Chapter 4. Case study 1 (Nail curing lamp)	• In order to characterise the potential blue light exposure for nail technicians and their customers, two commercially available LED nail lamps were used to simulate the L_B and D_B. • Field observations of tasks for nail technicians • Experiments based on exposure scenarios	Fluorescent or LED UV lamps are used in manicure and pedicure salons to cure nail coatings. Previous research has focussed on potential skin damage and cancer risk from UV radiation and not potential blue light-induced damage to visual photoreceptors. There are no data on time activity patterns for exposure assessment for nail technicians. Exposure assessments were conducted with a customised spectroradiometer, using a scenario-based approach (typical/worst). Time activity patterns were established by observation in seven nail salons in Adelaide. It was found that even under worst case conditions, the D_Bs were below the current guidelines promulgated by the ICNIRP. Direct viewing of these intense blue LEDs for extended periods will entail greater risk.
Chapter 5. Case study 2 (Video production studio)	• The exposure assessment of complex multi-light source environment and the determination of the OVF and exposure time activity patterns.	Video production studios are being used in many universities for the purpose of recording videos and there are various types of blue/white light sources used in the studios for high video quality. Using three different exposure scenarios during a 1-hour recording session, the exposure assessment of a presenter(s) was conducted. All D_Bs of the exposure scenarios were within the permissible level (10^6 J/m^{2}sr), but the LED spotlights exceeded the limit of L_B, 100 W/m^{2}sr. Based on these results, the LEDs in the studio are not likely to cause damage to the retina unless the source was directly viewed. However, assessment of exposure to light sources in the studio is difficult because of various ranges of

		the presenter's OVFs and different types of recording situations (e.g. gaze directions, recording styles or numbers of presenters).
Chapter 6. Case study 3 (Dental curing lamp)	• The exposure assessment of a handheld dental curing lamp which is an intense blue light source in a dental simulation clinic • Observations of training courses for second year dental students • Experiments based on exposure scenarios	Dental curing is achieved by intense blue light sources used for the curing of composite resins. Dental students repeatedly use these handheld lamps as part of simulation clinics and must be able to cure resins at various angles within the mouth of a mannequin. Students undertook curing procedures with both limited supervision and limited awareness of the blue light hazard. The D_{BS} did not exceed the limit of the ICNIRP guidelines, however, some L_{BS} often exceeded the limit of L_B, 100 W/m^2sr Training should include more detailed information on the blue light hazard. Blue-light protective glasses should be worn by students and professionals, and proper techniques to minimise exposure to this type of light, need to be taught Consideration could be given to the use of an alternate colour co-annular light source for teaching purposes, if not for more general use.
Chapter 7. General Discussion	• The novelty of the research and main findings in the framework of Work-Worker-Workplace are discussed and strengths and limitations are described.	The blue-weighted spectral radiance dose (D_B) depends on workers' OVFs, direct viewing angles and time/activity patterns of the blue light exposure. Young workers under 25 years of age and new workers are likely to have less awareness about safety issues and may be more vulnerable to blue light exposure. There are various blue light sources used in many workplaces and these need to be assessed, as part of lighting surveys.

		Epidemiological studies into the prevalence of eye related damage of workers and more information regarding exposure time activity patterns of blue light sources in the occupational visual field are needed. Smartphone light meter applications and the Google Street View application are available for preliminary lighting surveys at low cost. Using the blue filter on the luminance meter and smartphone light sensor, the blue light hazard function (BLHF) luminance and illuminance were measured and their results were compared to the values from a professional luminance meter and illuminance meter. In addition, new smartphone lighting applications for visual field information and measurement of luminance and L_B were tested.
Chapter 8. General conclusions and Recommendations	• Conclusions from the outcomes of the narrative literature review, three case studies and additional experiments • Recommendations for occupational health professionals, manufacturers and future researchers.	Due to the number of variables in various lighting environments in workplaces, exposure assessment of blue light is very complex. Exposure time activity patterns and workers' individual OVFs need to be considered. All D_{BS} in three case studies did not exceed the limit, 10^6 J/m^{2}sr. However, LED spotlights and a dental curing lamp did exceed the radiance limit of 100 W/m^{2}sr. Blue-light filtered glasses or shields can be effective in minimizing exposure. Use of eye protectors (e.g. blue filtering glasses or shields) for workers is an important means of control. Occupational health and safety professionals should understand the classifications of types of light sources in the workplace and understand the

		protective equipment needed. Manufacturers should consider safety design for reducing exposure to blue light. Finally, systematic and epidemiological studies are needed to provide further data on the risks of exposure to blue light in the workplace.
Appendix A. Assessment of blue light sources in the workplace	• Appraisal of various light sources	For preliminary experiments, emission of various light sources was characterised and the blue light component considered in the context of likely exposure durations and angles. In addition, blue-weighted luminance was measured using a blue filter.
Appendix B. Use of mobile phones for workplace lighting environment assessments	• Smartphone applications (light meter apps & Google Street View app) for initial lighting surveys	The Google Street View (GSV) app provides 3-Dimensional (3D) images and can be used for lighting surveys. A variety of smartphones using Android and IOS operating systems were used for illuminance measurements. The results were compared with professional lux meter in a mock up office. The values of the illuminance differed depending on distances or the types of light sources, however, the variations decreased as distance from light sources increased. Light meter apps were originally created for a camera, and not developed to identify the spatial information of the workplace or to measure lighting environments. Therefore, it is premature to use the apps for the assessment of the lighting survey in the workplace. However, it is expected that the further development of a specific light meter application can substitute for a professional lux meter.

Appendix C. Attenuation of blue light using eye protection	• Measurement of the blue light filtering efficiency of eye protective glasses	The blue light attenuation characteristics of four protective glasses were assessed using five LED light sources. Two blue protective safety glasses filtered most of blue wavelengths and the sunglasses also reduced blue light up to 50 %. However, due to the reflections on the surface of the glasses, the clear UV protective safety glasses showed two times higher values of the L_{BS} of the dental curing lamp and nail curing lamps than the original L_{BS}.

Chapter 1: General Introduction

This chapter presents background about the link between blue light exposure and health effects focussed on the assessment of blue light sources used in workplaces.

It introduces the concept of the *occupational visual field (OVF)* within which the blue light exposure may lead to retinal damage.

1.1 LIGHT

1.1.1 Light and optical radiation

Light is a visible form of electromagnetic (EM) radiation. Optical radiation encompasses light as well as ultraviolet (UV) and infrared (IR). According to the International Electrotechnical Commission (IEC 62471), optical radiation is classified into UV-A (315 - 400 nm), UV-B (280 - 315 nm), UV-C (100 - 280 nm), visible light (400-780 nm), IR (IR-A, 780 nm – 10,000 nm) (AS/NZS IEC 62471:2011) (Figure 1.1).

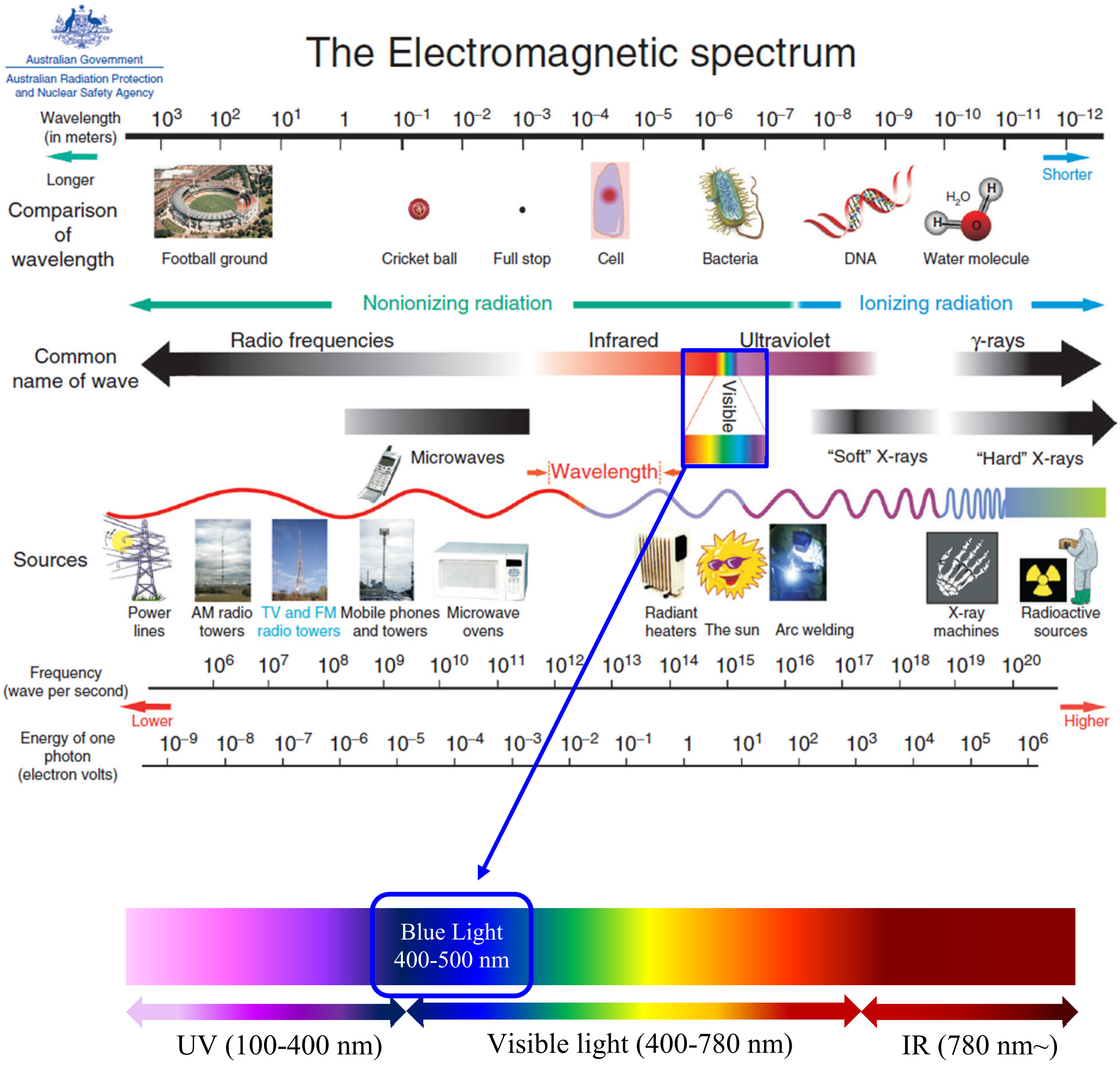


Figure 1.1 The electromagnetic spectrum (Source by Wood & Karipidis, 2016)

1.1.2 Light transmission through the eye

The human eye responds to wavelengths from 380 to 740 nm (Starr, Evers, & Starr, 2006) but the amount of light that reaches the photoreceptors can be modified by ocular organs. The cornea and the crystalline lens that help the eye focus are relatively transparent to visible light but absorb most of UV radiation ranging from 400 to 100 nm (Figure 1.2) and the parts of IR radiation at 980, 1200, and 1,430 nm.

Other optical radiation ranging from 1,400 to 10,000 nm can be cut by the vitreous humour (Barker & Brainard, 1991). With regard to visible light transmission to the retina, the opacity of the lens and vitreous humour increase with age thus reducing the amount of light reaching the retina (Hunter, Morgan, Merigan, Sliney, Sparrow & Williams, 2012).

The retina located in the back of the eyeball is the most important ocular organ of our vision. The retinal photoreceptor cells are very sensitive to light - they contain photopigments which trigger neural impulses. We distinguish images via the retina (Cline, Hofstetter, & Griffin, 1997). Retinal damage means vision impairment or even loss of vision.

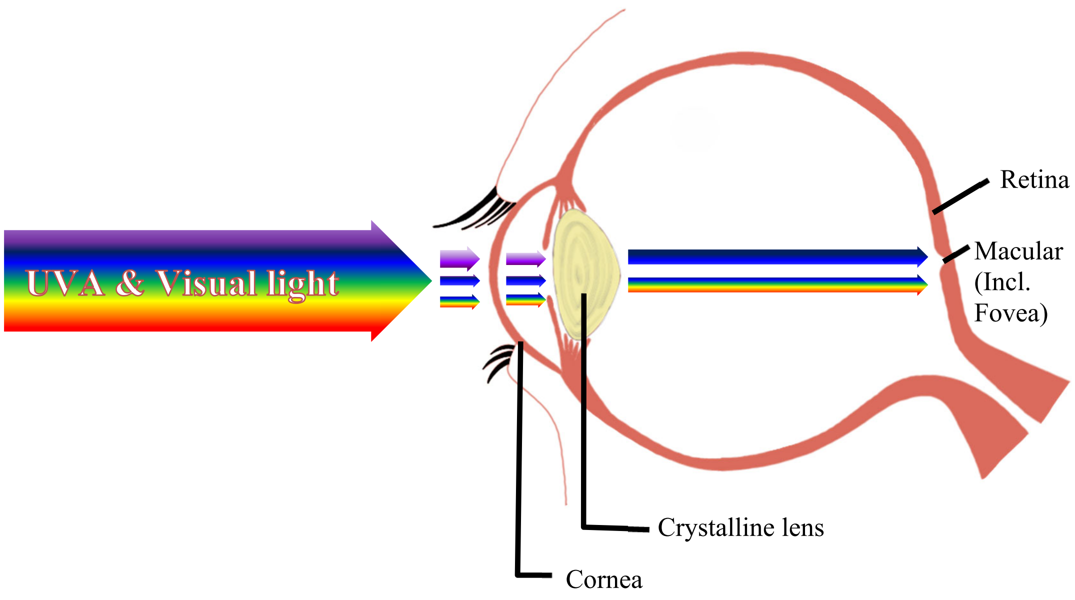


Figure 1.2 Light transmission of the human eye

1.1.3 Functions of the retina for visual acuity

The retina is about 1094 mm^2 and this is approximately 72 % of the area inside the eyeball when the average of axial length of the human eye is 22 mm (Kolb, 1995). The retina has ten layers and its most important roles are for detecting light and sending the detected light signals to the brain. The macula, which has oval-shaped, yellow-pigmented area on the central retina, includes photoreceptors, called rods and cone. These photoreceptors contain photopigments that undergo a chemical change when they absorb light. The diameter of the macula is around 5.5 mm (Provis, Penfold, Cornish, Sandercoe, & Madigan, 2005). There are approximately 90 million rods and 4-5 million cones in the human retina and depending on the area of the macula, the distribution of cones and rods are very different (Levin, Nilsson, & Ver Hoeve, 2011). The fovea is a small depression and is located in the central macula. It is the location with the highest sensitivity and provides our central visual acuity through cone photoreceptors (Skalicky, 2016). Rods are distributed at around 20 degrees of the macular predominantly and then show a decline gradually toward the periphery of the retina (Figure 1.2). These two photoreceptors detect the light and trigger neural impulses, passing visual signals to ganglion cells that carry information to the brain (Levin, Nilsson, & Ver Hoeve, 2011).

1.2 LIGHTING IN WORKPLACES

Light is essential for many workplace tasks, but the level and quality of lighting are important. Appropriate lighting increases productivity, whereas poor lighting reduces productivity and may compromise safety (AS/NZS 1680.1: 2006, Chung & Burnett, 2000).

Lighting in indoor environments is typically controlled by the provision of artificial light sources.

1.2.1 Basic types of interior lighting

In terms of interior lighting, there are generally three types of lighting: general or ambient lighting, accent lighting and task lighting (Innes, 2012) (Figure 1.3).

General or ambient lighting (natural and artificial)

General lighting is the primary source of light in office areas, commercial areas etc. It is the system of evenly lighting the entire space by placing the lighting fixture at intervals and at certain heights. This usually involves ceiling lamps, downlights, track lights, floor lamps or chandeliers.

Ambient lighting takes the form of indirect illumination from the surface of a wall or a ceiling, using reflected light.

Task lighting

Task lighting such as a portable desk lamp, has various lighting directions for different kinds of task, e.g. reading, typing, assembling parts, writing, drawing, near work or cooking. Task lighting alone may cause eye strain or eye fatigue due to the contrast between light and shade and thus, general or ambient lighting is generally used with task lighting.

Accent lighting

Accent lighting is used to highlight or draw attention to a particular object such as art or an architectural feature, a piece of furniture, a sculpture or a plant. Many different types, sizes and colour of light sources are used to accentuate a specific subject.

These three basic types of lighting - general or ambient lighting, task lighting and accent lighting, are applied to the interior design for performing tasks easily and comfortably. The balance between ambient, task and accent lighting is visually important.

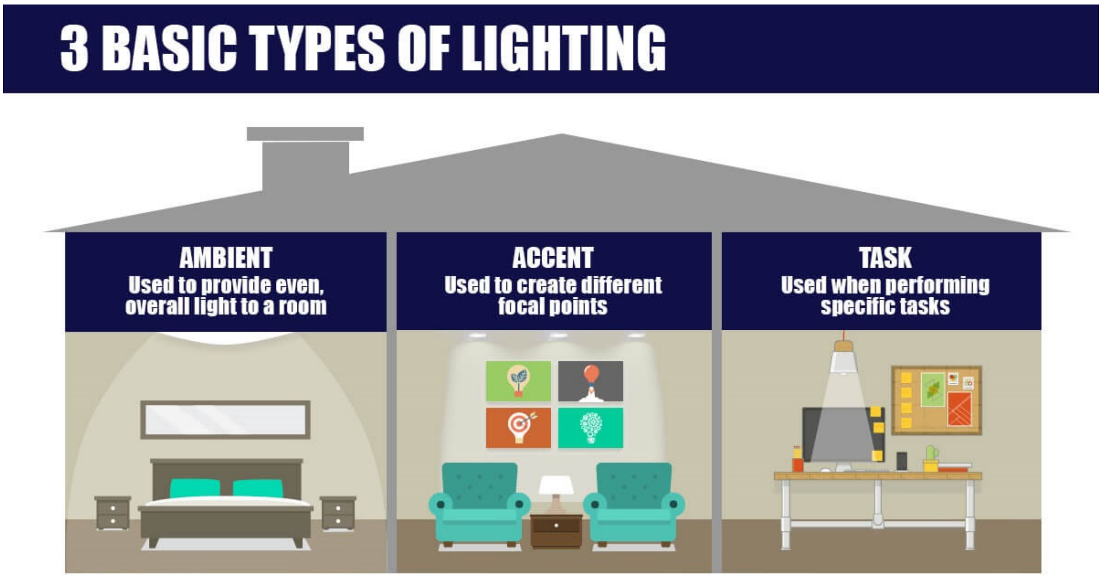


Figure 1.3 Three basic types of lighting
(Photo by https://www.camtecelectrical.com.au/wp-content/uploads/2017/09/3-basic-types-of-lighting-infographic-Linkedin-EN.jpg)

1.2.2 Hand held lighting

Hand held light sources are used for a variety of purposes in workplaces, e.g. ophthalmoscope for checking inside the fundus of the eye, dental curing lamps for polymerization of light cure resin based on composites etc. (Figure 1.4).

These hand held light sources are portable and very easy to use, however, due to different directions, distances and angles depending on user's hand movements, it is very complex to determine the measurement of the amount of light that enters the eye. For this, the study also focused on exposure assessment of a dental curing lamp based on actual exposure scenarios in case study 3 (Chapter 6).

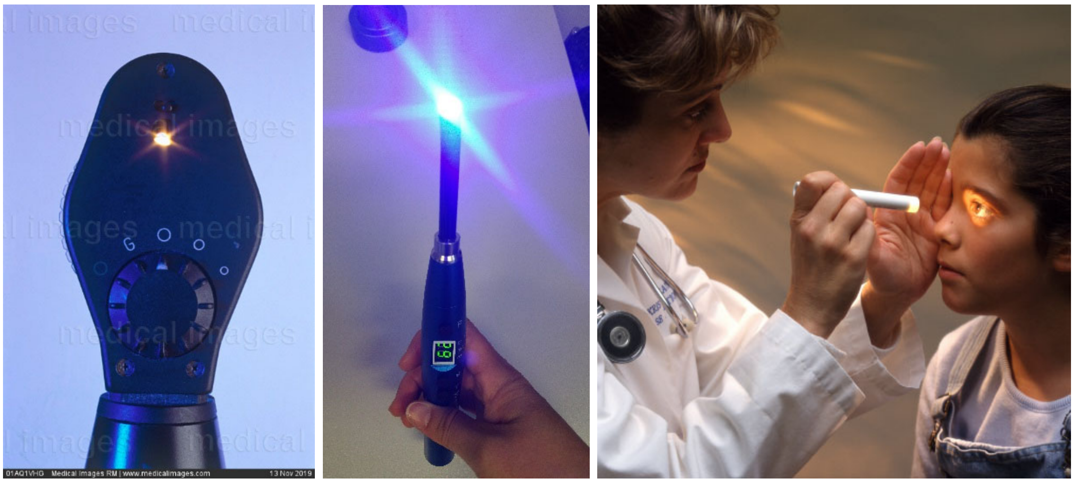


Figure 1.4 Examples of hand held light sources in medical fields
(from left to right: ophthalmoscope, dental curing lamp, pocket penlight for external eye exam)
(Photos by
- https://www.medicalimages.com/stock-photo-image-image15140595.html
- https://www.churchofjesuschrist.org/media-library/images/eye-doctor-examining-girl-healthcare-75562?lang=eng)

1.2.3 Types of workplaces and lighting requirements

There is a diverse range of workplaces, and many forms of recommended lighting. The standards, AS/NZS 1680 series, provide information about safety and appropriate lighting in workplaces. Table 1.1 shows the classification of AS/NZS 1680 series according to types of workplaces (AS/NZS 1680.1, 2006).

Table 1.1 AS/NZS 1680 series according to types of workplaces

Workplace	Office	Non-office-commercial	industrial	outdoor
Standard series (AS/NZS 1680)	**1680.2.2** Specific applications: Office and screen-based tasks	**1680.2.1** Specific applications – Circulation spaces and other general area	**1680.2.4** Industrial tasks and processes	**1680.5** Part5: Outdoor workplace lighting
	1680.2.3 Specific applications: Educational and training facilities		**1680.2.5** Hospital and medical tasks	
Examples of workplaces	Office room, workstations for reading, writing, filing, drafting and screen-based tasks, educational facilities such as classrooms or libraries.	Retail stores, corridors or carparks	Factories, bakeries, carpet and clothing manufacture, food processing, foundries furniture factories or medical-related workplaces such as treatment areas or operating rooms	General outdoor tasks

1.2.4 Different types of lamps and luminaires

There are four main types of artificial light sources.

Incandescent lamps

An incandescent lamp, which emits light caused by heating the carbon filament, was invented by Thomas Edison in 1879 (Friedel, 2010). This small bulb was used for a variety of uses from general light service (GLS)[1] lamps to a decoration light bulb. It marked the start of mass-production of artificial light sources. However, incandescent lamps are very inefficient as around 95 % of the power is wasted as heat. There is now a greater emphasis on more efficient light sources, particularly in Europe (Tetri, 2015). The Australian Government decided to phase out the use of inefficient incandescent light bulbs from 1 February 2009. It encourages the use of CFLs or LEDs as an alternative light source (Equipment Energy Efficiency E3 Program, 2018).

Fluorescent lamps

Fluorescent lamps are low-pressure mercury lamps and were developed to address the disadvantages of incandescent lamps. They generate less heat, are more efficient and are widely used in offices, schools, homes and factories. By the early 1990s, fluorescent lamps were in general use and stimulated interest in energy efficiency (DeMille, 2007). Compact versions (CFL) are available. On the downside, there are several issues such as photosensitive epilepsy and migraine from the flickering, or mercury exposure from broken fluorescent lamps

---

[1] General lighting service (GLS) lamps: “Term for lamps intended for lighting spaces that are typically occupied or viewed by people. Examples would be lamps for lighting offices, schools, homes, factories, roadways or automobiles.” (AS/NZS IEC 62471, 2011)

Electric discharge lamps

Electric discharge lamps are efficient and include mercury, sodium and metal halide lamps. They have high light outputs and commonly used for street lighting, car parks or warehouses.

Light-Emitting Diodes (LEDs)

A LED is a semiconductor light source that emits light when subjected to an electric current. Compared to incandescent or fluorescent lamps, they have high energy-efficiencies with a long life. Importantly, LEDs can be incorporated into various products in different colours, shapes and sizes and used for a variety of purposes from general light sources to specific purposes such as nail curing lamps or dental curing lamps.

Figure 1.5 shows spectral radiances of different types of light sources and more detailed measurement information about emission characteristic of typical light sources used in workplaces are described in Appendix A1.

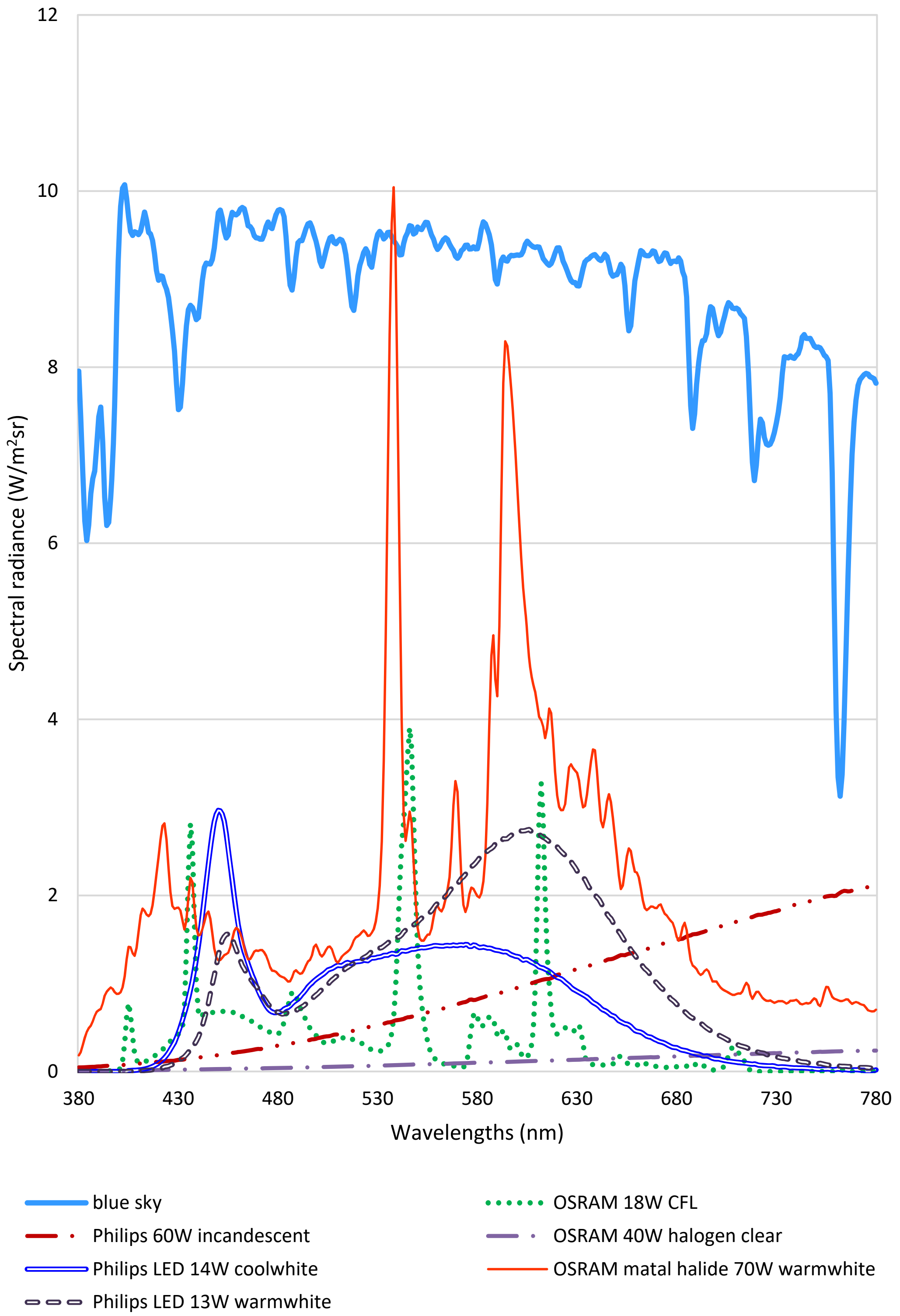


Figure 1.5 Spectral radiances of typical light sources measured by Specbos 1211UV (measurement distance between typical light sources and a spectroradiometer: 100 cm, excepting blue sky (∞))

1.3 HEALTH EFFECTS FROM EXPOSURE TO LIGHT

1.3.1 Visual effects – Retinal damage

As mentioned above, the retinal photoreceptors, can detect light and convert the light stimulus into electrical impulses (Starr, Evers, & Starr, 2006).

However, there are two types of retinal damage from light exposure: photochemical and photothermal damage.

- *Photochemical damage* is the photoreceptor injury caused by short wavelengths ranging from 380 - 550 nm and could be potentially arise from very bright blue-rich artificial light sources such as metal halide lamps and LEDs in workplaces. Generally, this is called the "blue light hazard". (ICNIRP, 2013; Sliney, Bitran, & Murray, 2012)

- *Photothermal damage* is the retinal thermal injury, mainly caused by near-infrared radiation from extremely intense infrared sources. Light exposure from incoherent sources is very unlikely to cause significant heating of the eye (Sliney, Bitran, & Murray, 2012).

Importance of vision

Sight is a major sense for humans and thus the loss of visual acuity can have a serious impact on the quality of life. In 2010 the World Health Organization (WHO) reported that there were 285 million people with vision impairment in the world (39 million people blind) and 82 % of all these blind people were over 50 years old. The main causes of blindness were reported to be cataracts, glaucoma, age-related macular degeneration (AMD), diabetic retinopathy and other diseases (World Health Organization [WHO], 2010). In 2009, a Vision 2020 Australia Report estimated that 66,500 Australians aged 40 or over were blind with the leading cause of blindness being AMD. It was also estimated that the total economic cost of Australians with vision impairment was $16.6 billion (Vision 2020 Australia, 2010). The estimated cost would be equivalent to 13.7 % of the total health spending ($121 billion) in that same year (Australian Institute of Health and Welfare [AIHW], 2018). Therefore, blindness and vision loss are not only public health problems, but also social and economic issues in our lives. The surprising fact, however, is that 75 % of the causes of all blindness are preventable and treatable (WHO, 2010).

Bourne et al. (2014) reported on the prevalence and cause of vision loss in high income countries, comparing data from 1990 and 2010. Figure 1.6 shows the percentage of the blindness and moderate and severe vision impairment (MSVI) decreased in 2010 compared with 1990 both in Australia and world-wide. However, the percentage of AMD increased in 2010 compared with 1990. Why more people are suffering from AMD is not known. AMD is the common retinal disease among people aged 50 or over. People with AMD can lose their central vision easily and there is currently no effective treatment for this (Macular Disease Foundation Australia, 2015). It is also very difficult to establish the exact pathogenesis but age, smoking, race, family history, and genetic factors are considered to be causal risk factors of AMD. Patients who have AMD in the early stages cannot recognise any health disorder because there are no symptoms (Macular Disease Foundation Australia, 2015).

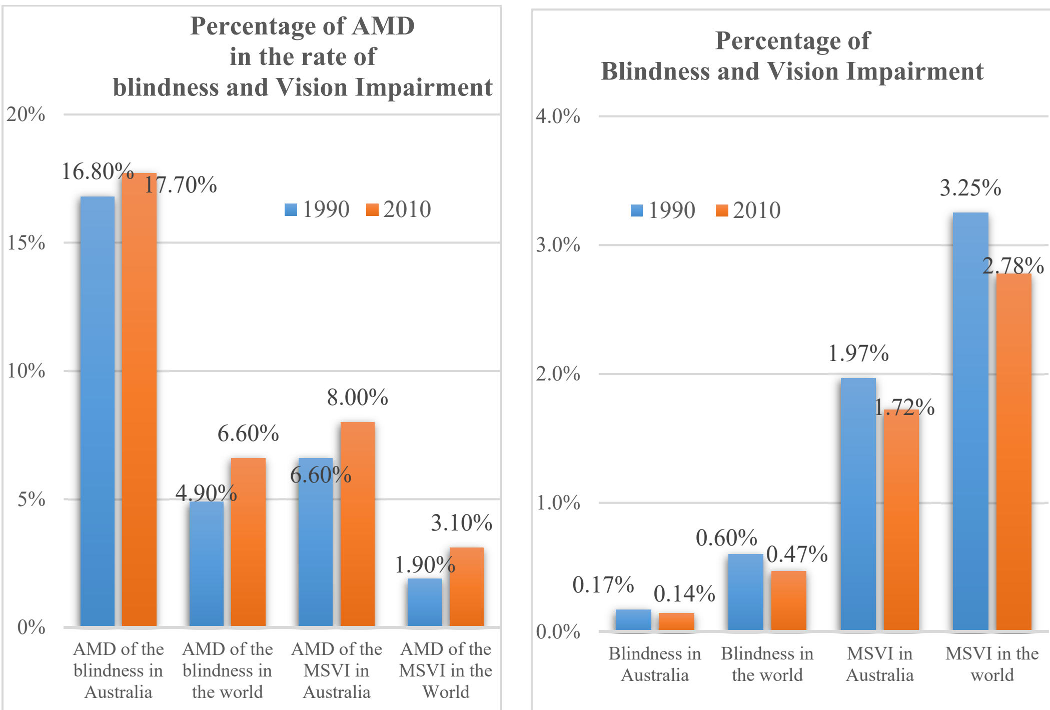


Figure 1.6 Cause of blindness and moderate and severe and vision impairment (MSVI) (Data by Bourne et al., 2014).

Historical background of retinal damage induced by light exposure

People have known for a long time that intense light can impair vision, and of course lasers, a special form of light which is intense by virtue of coherence, can burn the retina very rapidly. According to the classical literature, Pheado of the scholar Plato, was afraid of being blinded from sun gazing during an eclipse by citing his former teacher, Socrates' philosophy (Plato, 2008). The scientist who had tested the retinal damage from natural intense light in 1867 was Czerny (Palanker, Blumenkranz, & Marmor, 2011). About 10 years later, a French scientist Dufour showed direct viewing of the sun could induce damage to the fovea of the retina through his assessment of retinal pathology (Dufour, 1879). In 1976, Ham found that a specific range of shorter wavelengths could irreversibly damage the retina. This was the origin of the so called blue light hazard (Ham, Mueller, & Sliney, 1976) (Figure 1.7).

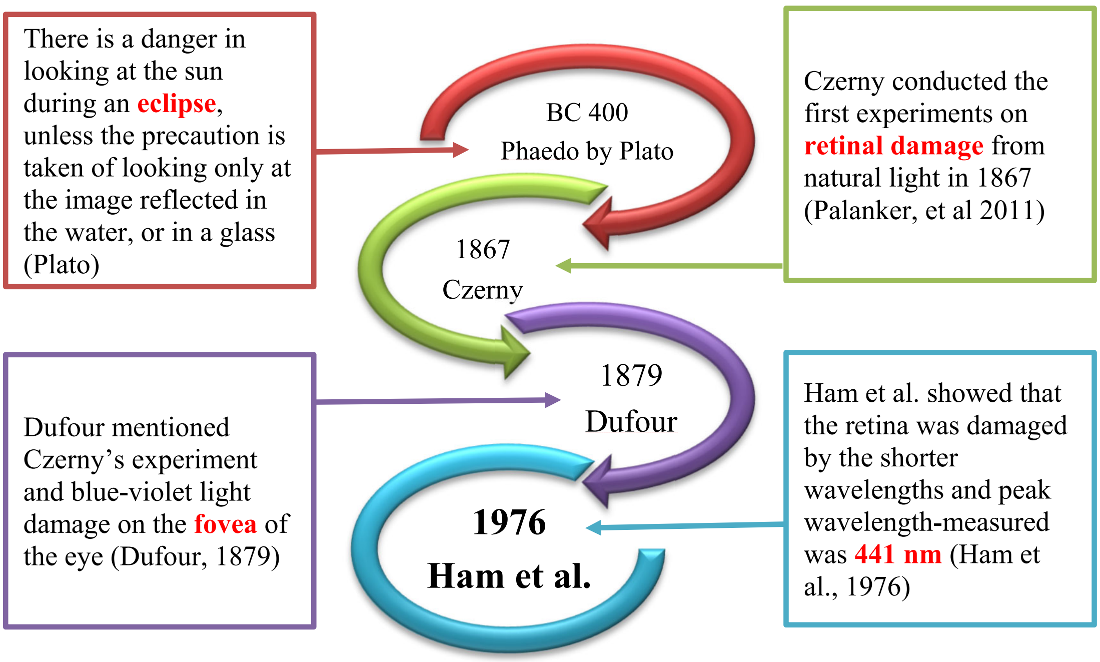


Figure 1.7 History of retinal damage from light exposure

Following Ham's research on animals, many researchers became interested in vision impairment by blue light sources, and a workplace exposure guideline was developed. It should be noted that this exposure limit was not based on the traditional approach of human epidemiology coupled with worker exposure measurements, but only on animal experimentation and later, human retinal cell studies (in vitro).

There is a body of evidence, through animal and human cell culture studies, that suggests that blue light can contribute to AMD. So far as is known, the light emitted at 441 nm is the peak wavelength most responsible for damaging the retina (Ham, Mueller, & Sliney, 1976). Noell et al. reported that short wavelengths can damage the retina cumulatively and the damage is dependent on temperature and exposure duration (Noell, Walker, Kang, & Berman, 1966). Recently, long term exposure to white light-emitting diodes (LEDs) has been identified as an issue for effects on the retina (Shang, Wang, Sliney, Yang, & Lee, 2014). However, there is still a lack of information about retinal photochemical damage (e.g. AMD) from intense artificial blue light exposure due to the limitations of the study of human populations.

In the only occupational epidemiological study of blue light exposure and AMD, fishermen (in the Chesapeake Bay) exposed to reflected bright sun light every day were found to have an increased risk of AMD. However, it is hard to define that it was specifically blue light exposure that induced AMD because the amount of blue light exposure was not measured objectively (Bressler, Bressler, West, Fine, & Taylor, 1989). Thus, there is weak evidence of a causal relationship between intense blue light exposure in the workplace and AMD.

In order to systematically assess exposure, it is important to determine a daily cumulative exposure. Directionality is highly important with respect to blue light and transmission to the retina as will be discussed in the next chapter. Direct and reflected light from one or more sources will also need to be taken into account. So far, there is little information due to the lack of detailed measurements. The technology for assessment is still being developed. Devices are available to assess radiance and irradiance but these are generally bulky and unsuitable for personal exposure measurements.

1.3.2 Non-visual effects

Circadian rhythm (ipRGCs, melatonin, sleep disorders)

Humans have a biological clock of approximately 24-hour duration and this cycle is called the “circadian rhythm”. Humans can sense light through their eyes, but, anatomically, the pineal gland also plays a role in detecting light and delivering light signals to the brain. Melatonin is a hormone which is naturally produced by the pineal gland. This is stimulated by darkness and inhibited by sunlight. Humans are active during the daytime and sleep at night. To eliminate waste matter, accumulated during the daytime, the body produces melatonin. This melatonin hormone induces not only sleep, but also speeds up metabolism and improve our activities during the day.

Blue light affects the circadian rhythm by discouraging the build-up of melatonin, a sleep-inducing metabolite (SCENIHR, 2012).

There is another factor which can change/affect the circadian rhythm. Melanopsin is a light-sensitive retinal protein and is found in the intrinsically photosensitive retinal ganglion cells (ipRGCs). The ipRGCs have a maximum sensitivity to light between 420 to 480 nm and are implicated in non-visual responses to light. Blue light with these short wavelengths can damage the ipRGCs and it is closely related to the problems with the circadian rhythm (Kolb, 1995).

Impairment of the circadian rhythm is linked to a number of diseases, e.g. breast cancer (night shift workers), sleep disorder, alertness, depression, cognitive performance, obesity, diabetes, etc. (James et al., 2017; SCENIHR, 2012).

1.4 BLUE LIGHT IN THE WORKPLACE

Emerging blue light exposure and occupational health issues

Blue light is a relatively high-energy form of visible (HEV) light from 400 to 500 nm and adjacent to ultraviolet in the visible spectrum (AS/NZS IEC 62471:2011). It is commonly emitted from light sources (e.g. self-illuminating computer monitors and normal interior lamps). It is also used for medical and therapeutic purposes (e.g. infant phototherapy).

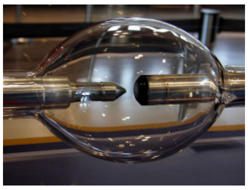
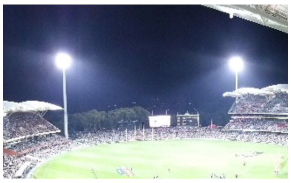
1.4.1 Types of blue light sources

Light sources can be classified into two groups; natural light sources such as the sun and artificial light sources such as incandescent lamps. With artificial light sources, increasing attention is paid to economical and brighter light sources. Lighting accounts for around 10-12 % of electricity usage in households, and 18–40 % in commercial premises in Australia (Energy Rating, 2016).

Since the 1980s metal halide lamps (and other forms of high intensity discharge lamps) have been popular in the lighting industry (Hordeski, 2004) because of their high light output. These have a strong blue light spectral component and are used for overhead lighting of industrial buildings, sports stadia, and commercial areas. In 2014, three Japanese scientists who invented a LED with enhanced blue wavelength light won the Nobel Prize in Physics (The Royal Swedish Academy of Sciences, 2014). Many countries including Australia currently prefer LEDs as their main artificial light sources because of low energy consumption.

In general, blue-rich wavelength white light sources emit significant blue light wavelengths (Shang, Wang, Sliney, Yang, & Lee, 2014). Therefore, there is a need to understand retinal exposures experienced and associated photoreceptor damage risks from certain artificial light sources. The American Conference of Governmental Industrial Hygienists (ACGIH) has described types of artificial light sources and likely applicable damage to the eye (American Conference of Governmental Industrial Hygienists [ACGIH], 2015) (Table 1.2).

Table 1.2 Example sources of artificial optical radiation and applicable TLVs (source - ACGIH, 2015)

*Source Type**	**Arc Sources** 	**Discharge Lamps**	**Fluorescent Lamps and LEDs**
	Arc welding; Arc lamps; Xenon-arc 		White-light and “black-light” fluorescent lamps; Visible or UV-A LEDs
Ultraviolet	Likely	Possible	Possible
Blue-Light	Likely	Likely	Possible

* “Likely and Possible”: levels of applicable damage to the eye
[#] Photos: https://en.wikipedia.org/wiki/File:Xenon_short_arc_1.jpg and https://en.wikipedia.org/wiki/Arc_welding#/media/File:SMAW.welding.navy.ncs.jpg)

1.4.2 Use of blue light in workplaces

Blue light is found in many places and can be used for a variety of purposes, such as medical treatment and beauty therapy, performing arts, aquarium lighting and insecticidal lamps. Stage lights are normally intense artificial light sources and the energy flux of blue light can be significant even when the light does not appear blue (O’Hagan & Khazova, 2011). Surgical lamps in operating rooms are also intense light sources emitting blue wavelengths (Dithmar, Hoeh, Amberger, Ruppenstein, & Ach, 2011).

Blue light sources in hospitals are typically used for treatment of jaundice in newborn infants or for the polymerization of dental composite resins (Pinto, et al., 2015; Price, Labrie, Bruzell, Sliney, & Strassler, 2016). Bright white light sources have been recently used for the treatment of depression such as seasonal affective disorder (SAD) (Gomes & Preto, 2015). Blue light can be also used for acne treatment (Dowdy & Sayre, 2013; Barbaric et al., 2018).

1.4.3 Workers who are more exposed to blue light sources

In the following section, the emphasis is on workers who may be exposed to intense blue light sources.

Workers at risk

These potentially include lighting technicians, retail and commercial workers, health professionals, welders, etc.

The number of workers at risk may be large. According to the Job Outlook website in Australia in 2015, the population of jewellery-related and photographic-related workers, who are exposed to various intense artificial light sources such as white LEDs or metal halides, may number 17,000 and 31,600 respectively. The number of welders who may be exposed to very strong light from arc welding also approaches 70,000. Beauty therapists (including nail technicians who use nail curing lamps emitting intense blue light) shows the rapid growth of employment (Job Outlook, 2015).

In the working environment job tasks will vary and the quantification of light exposure in the visual field of all tasks is difficult. Workers have different visual fields and exposure conditions (durations, types of light sources) in their workplaces. In order to systematically assess exposure, it is important to consider light projected on the macula. For long term effects and chronic exposure scenarios, a daily cumulative exposure assessment is warranted.

1.5 EXPOSURE CRITERIA

1.5.1 Photometry and radiometry

The measurement of light can be divided into two main categories: *radiometry and photometry*. Radiometry is pure energy assessment, and expressed as irradiance (W/m^2) and radiance (W/m^2sr) (Figure 1.8). As a complement to radiometry, photometry accounts for human visual responses to radiant energy and expressed as illuminance (lux) and luminance (cd/m^2) (Freeman, Hull, & Charman, 2003) (Figure 1.9, Table 1.3).

Table 1.3 Basic terms of illumination and units

	Radiometry quantity Symbol (unit)	**Photometry quantity Symbol (unit)**
Flux	Radiant flux ϕ (W)	Luminous flux ϕ_v (lm)
Angular intensity	Radiant intensity I (W/sr)	Luminous intensity I_v (lm/sr)
At a surface	Irradiance E (W/m^2)	Illuminance E_v (lm/m^2 or lx)
At a source	Radiance L (W/m^2sr)	Luminance L_v (cd/m^2)

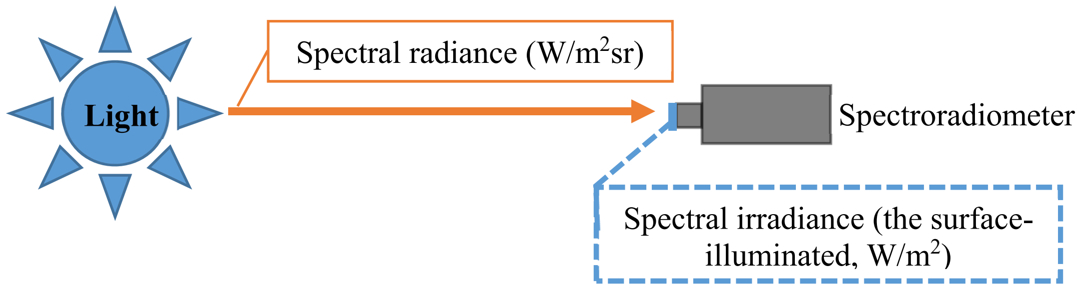


Figure 1.8 Spectral radiance (straight line, colour orange) and spectral irradiance (dotted line, colour blue)

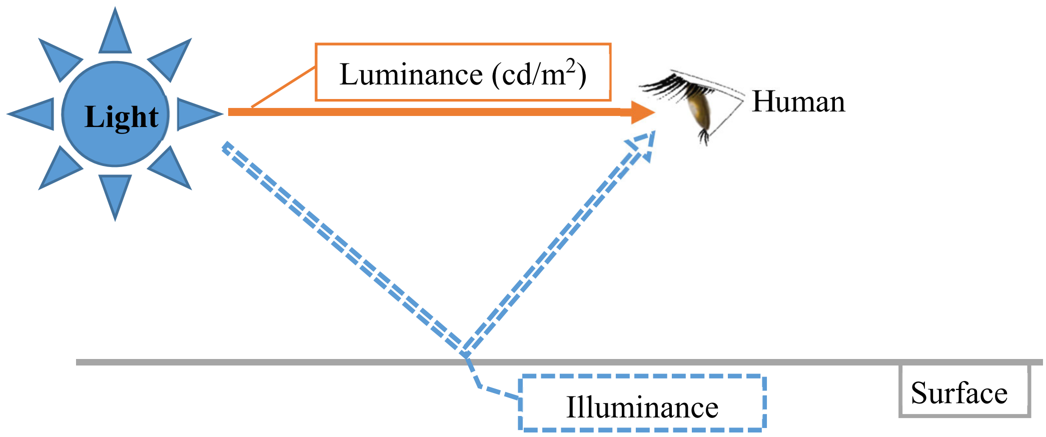


Figure 1.9 Luminance (straight line, colour orange) and illuminance (dotted line, colour blue)

1.5.2 ACGIH TLV & ICNIRP guidelines

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines and the American Conference of Governmental Industrial Hygienists threshold limit value (ACGIH TLVs) have exposure criteria for blue light exposure in the workplace (ACGIH, 2015; International Commission on Non-ionizing Radiation Protection [ICNIRP], 2013). These are essentially derived from animal studies. The blue weighted spectral radiance (L_B) and the radiance dose (D_B) are calculated using the equations based on the ICNIRP guidelines. ICNIRP guidelines provide the exposure limits for the effective radiance and the radiance dose according to the durations of blue light exposure. For viewing durations up to 10,000 sec (2.8 hours), the radiance dose (D_B) should be under 10^6 J/m^{2}sr and the radiance limit is 100 W/m^{2}sr, if the exposure duration is 10,000 sec or more (Equation 1.1 Formulae relating to blue light hazards from ICNIRP guidelines and ACGIH TLVs.).

$$L_B = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta\lambda$$

$$D_B = L_B \cdot t$$

$$L^{EL}{}_B = 100 \text{ W/m}^2\text{sr}$$

$$D^{EL}{}_B = 10^6 \text{ J/m}^2\text{sr}$$

L_B : Effective radiance of blue light (W/m^2·sr)
D_B : Effective blue light radiance dose (J/m^2·sr)
L_λ : Spectral radiance (W/m^2·sr·nm)
$B(\lambda)$: Blue light hazard function
$\Delta\lambda$: wavelength interval (nm)
t : Exposure duration (seconds)
$L^{EL}{}_B$: Exposure limit of effective blue light radiance. (t > 10,000 s)
$D^{EL}{}_B$: Exposure limit of effective blue light radiance dose. (0.25s ⩽ t < 10,000s)

Equation 1.1 Formulae relating to blue light hazards from ICNIRP guidelines and ACGIH TLVs.

These criteria were applied to all simulation experiments based on field observations in Chapter 4 to 6 and more detailed information about these guidelines are mentioned in Chapter 4 to 6.

Blue light damage to photoreceptors (called “photochemical damage”) is suggested to be an energy-based effect and measured in radiometric terms. It is also wavelength specific, hence a weighting scheme is needed – like *“A weighted” noise measurements*. Maximum damage is effected at around 440 nm. The risk of the photochemical damage is related to the radiance of the light source as well as the size of the image of the source that is focused on the retina. The blue-weighted spectral radiance (L_B) can be calculated using the blue light hazard function ($B(\lambda)$) ranging from 300 to 700 nm (Figure 1.10) (ICNIRP, 2013).

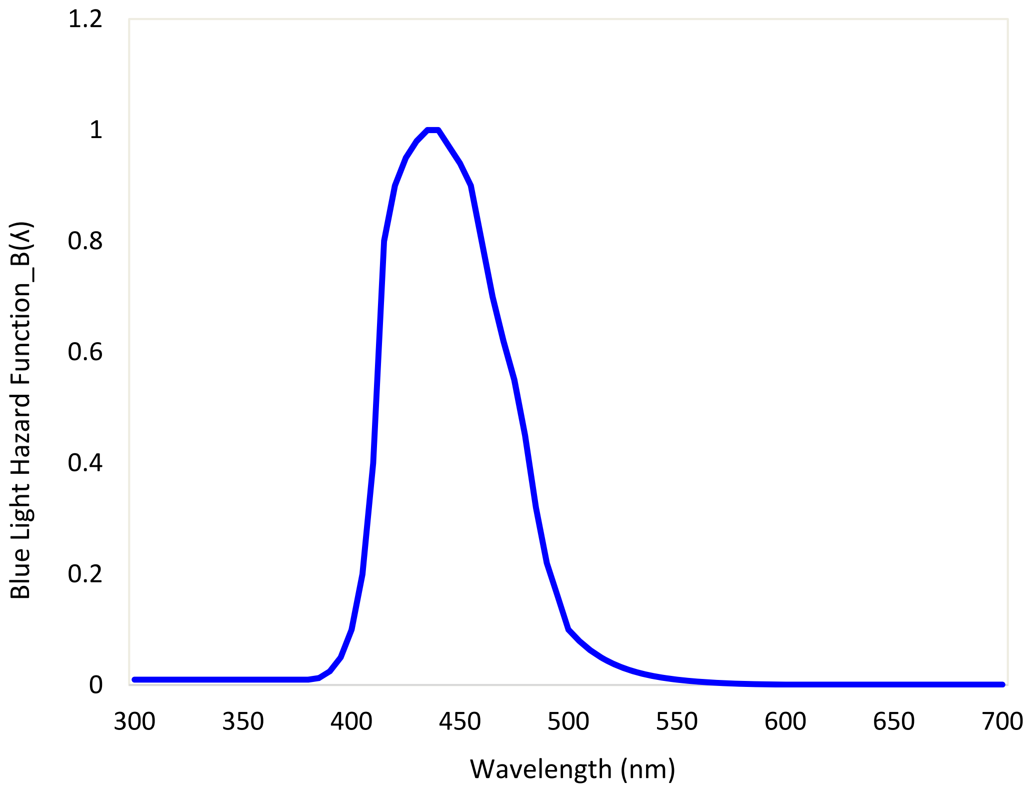


Figure 1.10 Blue light hazard function (B(λ)) for normal eyes (Data by ACGIH TLVs)

1.5.3 Photobiological safety of artificial optical radiation (levels of risk groups)

Lamps have been classified according to blue weighted radiance output. AS/NZS IEC 62471 (2011) provides the lamp classification and consists of four groups ranging from an exempt group (risk group 0) to a high risk group (group 3) (Table 1.4).

Table 1.4 Classification scheme of risk groups from blue light exposure (AS/NZS IEC 62471:2011)

Risk Group	The extent of the risk	Example
Exempt group (RG0)	Non-Risk	Effective blue light radiance (L_B) within 1,000 sec
Risk Group 1 (RG1)	Low-Risk	Effective blue light radiance (L_B) within 100 sec
Risk Group 2 (RG2)	Moderate-Risk	Effective blue light radiance (L_B) within 0.25 sec
Risk Group 3 (RG3)	High-Risk	The excess of the limits for Risk Group 2

With this classification in Table 1.4, the potential blue light risk and the maximum permissible exposure duration can be determined, however, labelling of the risk groups on artificial light sources is not required in workplaces. Thus, more detailed information or regulations about the potential retinal damage from blue light exposure are currently needed.

1.5.4 Definitions of terms

Key terms in photometry and radiometry are given in Table 1.5.

Table 1.5 Definitions of terms
(AS/NZS 1680, 2006; Soderberg et al., 2016; Zhu et al., 2017)

Term	Definition	Unit
Illuminance	Luminous intensity Brightness of the light emitted from the area of the illuminated surface (namely, the luminous flux).	Lux (lx)
Luminance	The physical quantity corresponding to the brightness of a surface (e.g. a lamp, luminaire, sky or reflecting material) in a specified direction. It is the luminous intensity of an area of the surface, divided by that area. Amount of light included in the solid angle	cd/m^2
Correlated Colour Temperature (CCT)	A way to describe the light appearance provided by a light bulb (lamp). The colour temperature of a light bulb (lamp) is assigned using the basis of correlated colour temperature (CCT).	K
Spectral radiance	Spectral radiance is the radiance of a surface per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength. These are directional quantities.	W/m^2sr
Spectral irradiance	The irradiance of a surface per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength. The two forms have different dimensions: spectral irradiance of a frequency spectrum is measured in watts per square metre per hertz ($W/m^2 \cdot Hz$), while spectral irradiance of a wavelength spectrum is measured in watts per square metre per metre (W/m^3), or more commonly watts per square metre per nanometre ($W/m^2 \cdot nm$).	W/m^2
Glare	The discomfort or impairment of vision experienced when parts of the field of view (e.g. lamps, luminaires) are excessively bright in relation to the general surroundings.	UGR index

1.6 METHODS OF BLUE LIGHT EXPOSURE ASSESSMENT

Assessment of exposure for retinal photochemical damage requires measurement of light that actually enters the eye and projected on the retina. The relevant visual field is defined anatomically and in the case of workers, it is the so-called occupational visual field.

1.6.1 Occupational visual field (OVF)

Humans have spatial visibility, called a visual field, from which objects can be detected and recognised. The averages of a binocular visual field are 60 – 75 degrees vertically and 160 – 200 degrees horizontally including 120 degrees of the central field overlapped by both eyes (Levin, Nilsson, & Ver Hoeve, 2011). The visual tasks define the occupational visual field. (Piccoli et al, 2004).

1.6.2 Measurement frame of OVF

Every worker has their own working environment, e.g. working distances and duration. Depending on distances between the eyes and light sources, various viewing angles of a worker should be considered in their OVFs while working. Based on the 'occupational fixation zones' (OFZ) described by Piccoli et al. (2004), the OVF can be determined using the areas of the human central vision (within 40 degrees) and applied to the exposure scenarios (Figure 1.11). The worker in the figure below is fixated on the screen, keyboard and document holder.

The evaluation of the blue light exposures in the selected workplaces described in Chapters 4-6 was carried out using the concept of the OVF.

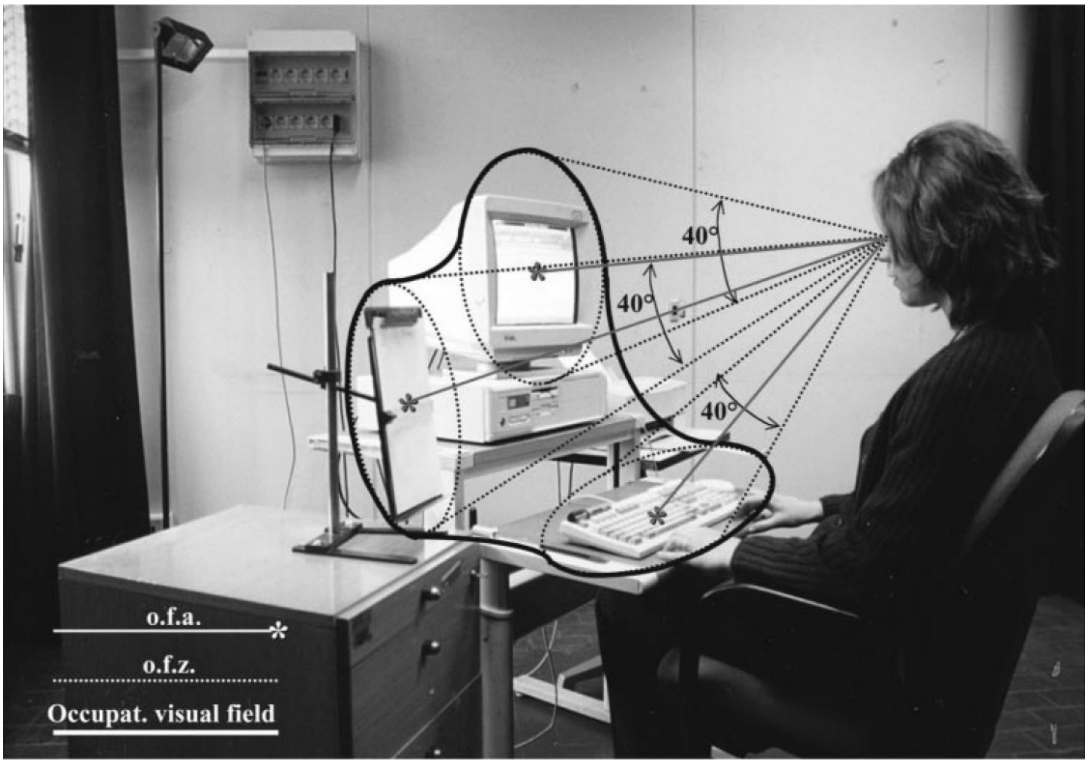


Figure 1.11 An example of the OVF of an office worker
(Photo - Piccoli et al, 2004)

1.6.3 Blue light sources in the OVF

The blue-light photochemical retinal damage can occur when workers are exposed to blue light sources located in their OVF.

Figure 1.12 shows the visual field of a worker who works behind a counter of a retail store, with metal halide lamps. She constantly looks at the checkout desk and customer(s) while working and there are roof-suspended lamps in her OVF (front central vision) when she looks at a customer or areas of the shop.

Figure 1.12 An example of the OVF of a staff in a retail store
(photo courtesy - Bruno Piccoli)

In another example, Figure 1.13 shows different exposure situations for a worker and a customer in a department store. When the worker looks up at the customer, two white coloured lamps are located in the worker's visual field and may affect her central vision.

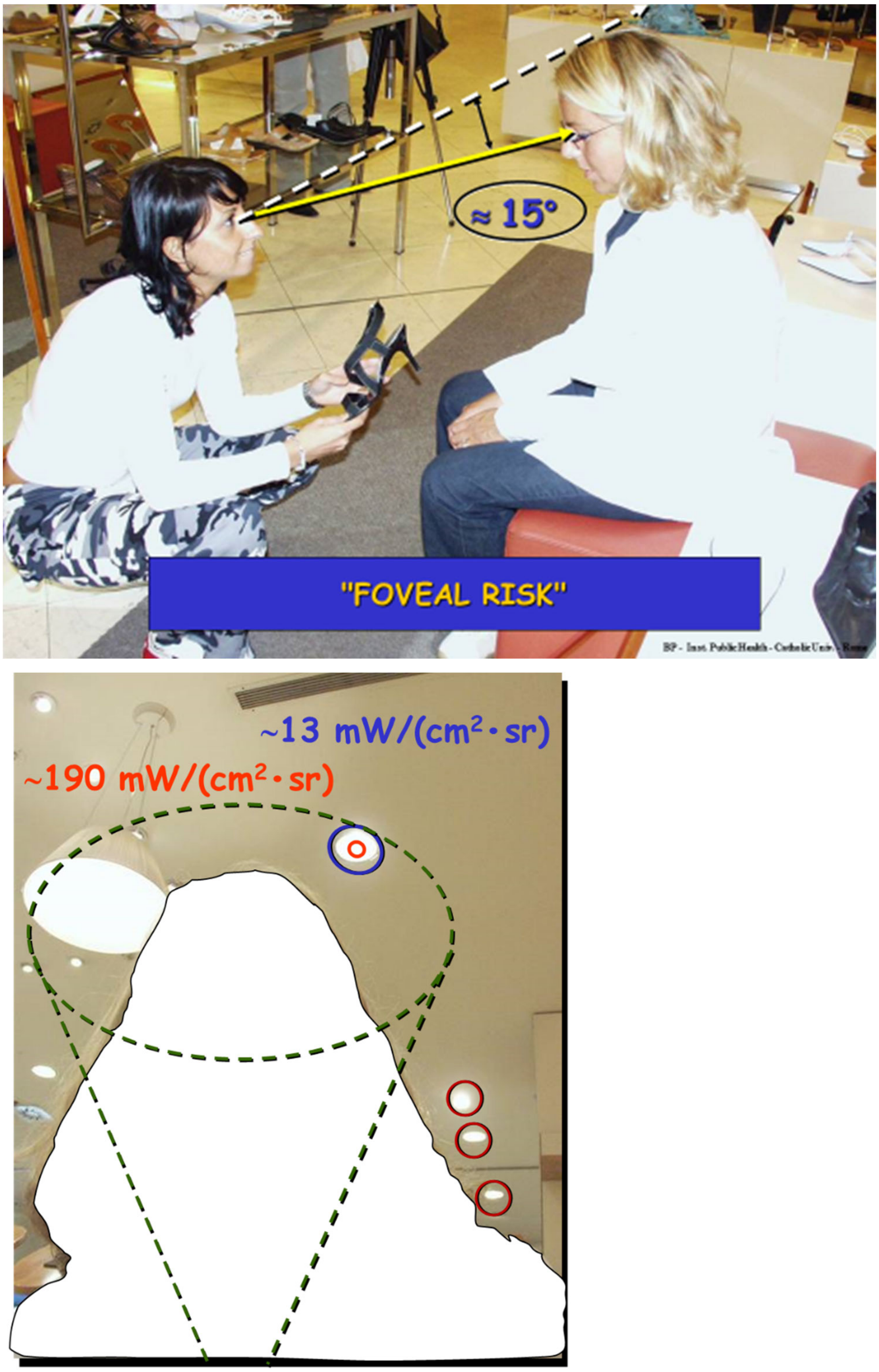


Figure 1.13 The OVF of a staff member of a department store and blue light sources within her OVF (photo courtesy - Bruno Piccoli)

1.7 BRIEF SUMMARY OF THE KEY ISSUES IN THIS CHAPTER

This chapter has described exposure to blue light and potential retinal risks.

Anecdotally, most occupational health professionals are unfamiliar with the blue light hazard. The literature is scattered across disciplines, and mostly in ophthalmology, optometry and health physics.

The next chapter is a more formal narrative literature review focused on potential blue light hazards in occupational settings. It is based on the following research question:

"What is the evidence that blue light in workplaces is capable of causing retinal damage?"

The narrative aligns with a conventional occupational health paradigm - namely Hazard Identification, Exposure Assessment and Control.

Chapter 2: Narrative Literature Review

This chapter is a narrative literature review of blue light hazards, exposures and controls. The evidence is scattered in multiple disciplines such as Medicine, Biology, Physics, Public Health, etc. A systematic search was done using bibliographic databases (e.g. PubMed, Scopus and Embase) and then, hand-searching, grey literature searching and other searching methods (e.g. forward and backward, author searching). The review underpins the methodology in Chapter 3 and the empirical case studies described in Chapters 4-6.

2.1 INTRODUCTORY REMARKS ON THE RETINAL HAZARD FROM BLUE LIGHT EXPOSURE

Close to two–thirds of people with vision impairment are over 50 and their eye condition can often be linked with chronic age-related changes of the eye (WHO, 2018). Degradation of the photoreceptors causes vision impairment, and damage to the fovea that is located in the middle of the macula leads to central vision loss (Levin, Nilsson & Ver Hoeve, 2011). Blue light can pass through the cornea and lens and reach the retina where intense exposure can damage the retinal photoreceptors, potentially exacerbating age-related macular degeneration (AMD) (Behar-Cohen et al., 2011; Schick et al., 2016; Wielgus & Roberts, 2012), one of the leading causes of blindness and vision impairment (Lim, Mitchell, Seddon, Holz, & Wong, 2012; Taylor, Hobby, Binns & Crabb, 2016; WHO, 2010). Risk factors for AMD are thought to include smoking status, age, gender, genetic factors and environmental factors (Lim, Mitchell, Seddon, Holz, & Wong, 2012) The prevalence and incidence of AMD show a continuously increasing trend associated with an aging population throughout the world (Bourne et al., 2014; Lim, Mitchell, Seddon, Holz, & Wong, 2012; Taylor, Hobby, Binns & Crabb, 2016). The progression of AMD is usually insidious and thus effective prevention is needed (U.S. Energy Information Administration [EIA], 2013).

Blue light exposure from the sun and intense artificial lighting sources is thought to be a risk factor for macular degeneration.

There are various artificial light sources that emit intense blue wavelengths in the workplace (see Table 1.2) and many workers can unknowingly be exposed to these light emissions. Since the 1990's, light-emitting diodes (LEDs) have been increasingly used as light sources, and these often have significant blue light components (Energy Rating, 2016; Siminovitch, 2010). It is unclear how much modern lighting contributes to AMD, especially in workplace situations.

Most workplace studies of blue light exposure have focused on occupations such as welders or medical personnel (Briggs et al., 1992; Okuno, Ojima, & Saito, 2010; Pinto et al., 2015; Price, Labrie, Bruzell, Sliney, & Strassler, 2016). However, recent research has also considered blue light emissions from low-energy light devices (e.g. computer monitors or smart phones) or general background light lamps (e.g. LEDs or compact fluorescent lights) (O'Hagan, Khazova, & Price, 2016). There is continued debate about potential long term degradation of the macula (Behar-Cohen et al., 2011; Huang et al., 2014; Wielgus & Roberts, 2012).

2.2 OBJECTIVE OF THE REVIEW

The Research question is:

What is the evidence that blue light in workplaces is capable of causing retinal damage?

The research question given above uses a **PI(C)O**[2] framework through the lens of public health. **P**opulation is the 'retina', **I**ntervention is 'blue light', and **O**utcome is 'Damage' from blue light sources (Table 2.1).

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[2] **PICO**: the paradigm of evidence-based medicine for clinical questions. The PICO acronym stands for **P**opulation/**P**atient/**P**roblem, **I**ntervention, **C**omparison and **O**utcome(s) (Huang, Lin, & Demner-Fushman, 2006).

Table 2.1 Framework for the research question

	Population	**Intervention**	**Outcome**	**Question**
Hazard	Retina (animals & human cells)	Blue light	Retinal damage (e.g. macular degeneration) Vision impairment Blindness	What is the evidence that blue light in workplaces is capable of causing retinal damage?
Exposure			Risk assessment Standards TLVs	
Controls			Health surveillance Regulation/Prohibition Sign/Warning Education Protective equipment Antidote Vaccination	

2.3 LITERATURE REVIEW SEARCH STRATEGY

Three different bibliographic databases (PubMed, Scopus, and Embase) were used to gather evidence. Initial yields were complemented with hand-searching, backward searching with key authors' names as well as forward searching. The major key words used for the databases searching were "blue light", "retina", "light emitting diode", "metal halide" and "work" (see Table 2.2 & 2.3). PubMed searches were conducted by the MeSH term and the other Scopus and Embase searches were done by abstracts and titles. However, as few articles were found relating to the workplace, a number of search terms were used.

Documents were identified and selected from a first search in September 2015. In the next two years some new studies related to blue light hazards were published and an additional search with the same search strategy was conducted in December 2017 and then, final searches were carried out in June 2019 (Table 2.2 & 2.3, Figure 2.1).

Table 2.2 Initial logic grid created in September 2015

		Hazard	Occupational Exposure	Occupational Control
PubMed	Key Words	Retina	Blue Light, LED, Metal-halide	Occupations[MESH] Health Occupations[MESH] Occupational Groups[MESH] Work[MESH] Employment[MESH]
	First searching	(retina*) AND ((blue light) AND (((LED) OR "light emitting diode") OR "metal halide")) Results: **60** articles		
	Second searching	((retina*) AND blue light) AND (((((Occupations[MESH]) OR Health Occupations[MESH]) OR Occupational Groups[MESH]) OR Work[MESH]) OR Employment[MESH]) Result: **19** articles		
Scopus	Key Words	Retina	Blue Light, LED, Metal-halide	Occupation* Work* Employ* Job*
	First searching	((retina*) AND ((blue light) AND (((led) OR "light emitting diode") OR "metal halide"))) Results: **126** articles		
	Second searching	((retina*) AND ((blue light) AND (((led) OR "light emitting diode") OR "metal halide")))) AND (TITLE-ABS-KEY(work* OR occupation* OR employ* OR job*)) Result: **19** articles		
Embase	Key Words	Retina	Blue Light, LED, Metal-halide	Occupation* Work* Employ* Job*
	First searching	(retina*) AND ((blue light) AND (((LED) OR "light emitting diode") OR "metal halide")) Results: **86** articles		
	Second searching	occupation* OR work* OR employ* OR job* AND retina* AND 'blue light' Result: **87** articles		

Table 2.3 Second logic grid created in December 2017 and used in June 2019

		Hazard	Occupational Exposure	Occupational Control
PubMed	Key Words	Retina	Blue Light, LED, Metal-halide	Occupations[MESH] Health Occupations[MESH] Occupational Groups[MESH] Work[MESH] Employment[MESH]
	Searching	(((retina*) AND ((blue light) AND (((LED) OR "light emitting diode") OR "metal halide")))) OR (((retina*) AND blue light) AND (((((Occupations[MESH]) OR Health Occupations[MESH]) OR Occupational Groups[MESH]) OR Work[MESH]) OR Employment[MESH])) Results: **123** articles		
Scopus	Key Words	Retina	Blue Light, LED, Metal-halide	Occupation* Work* Employ* Job*
	Searching	(((retina*) AND ((blue AND light) AND (((led) OR "light emitting diode") OR "metal halide")))) OR ((retina*) AND ((blue AND light) AND ((led OR "light emitting diode") OR "metal halide")) AND (work* OR occupation* OR employ* OR job*)) Results: **188** articles		
Embase	Key Words	Retina	Blue Light, LED, Metal-halide	Occupation* Work* Employ* Job*
	Searching	((retina*) AND ((blue light) AND (((led) OR "light emitting diode") OR "metal halide"))) OR ((retina*) AND ((blue light) AND ((led OR "light emitting diode") OR "metal halide"))) (AND (work* OR occupation* OR employ* OR job*)) Result: **261** articles		

Inclusion and exclusion criteria are shown in Table 2.4.

Table 2.4 Inclusion and Exclusion Criteria for the searches

Inclusion	Exclusion
All study designs	
All fields of work	
Retinal injuries	Other eye diseases excepting retinal diseases
Artificial blue light sources	Natural light sources only
	Other light wavelengths such as UV, IR or laser
Ocular radiation	
English only	

The yield is depicted in a PRISMA 2009 flow diagram (see Figure 2.1) (Moher, Liberati, Tetzlaff, Altman, & Prisma Group, 2010). To manage the yield, EndNote X7 and the Excel program were used.

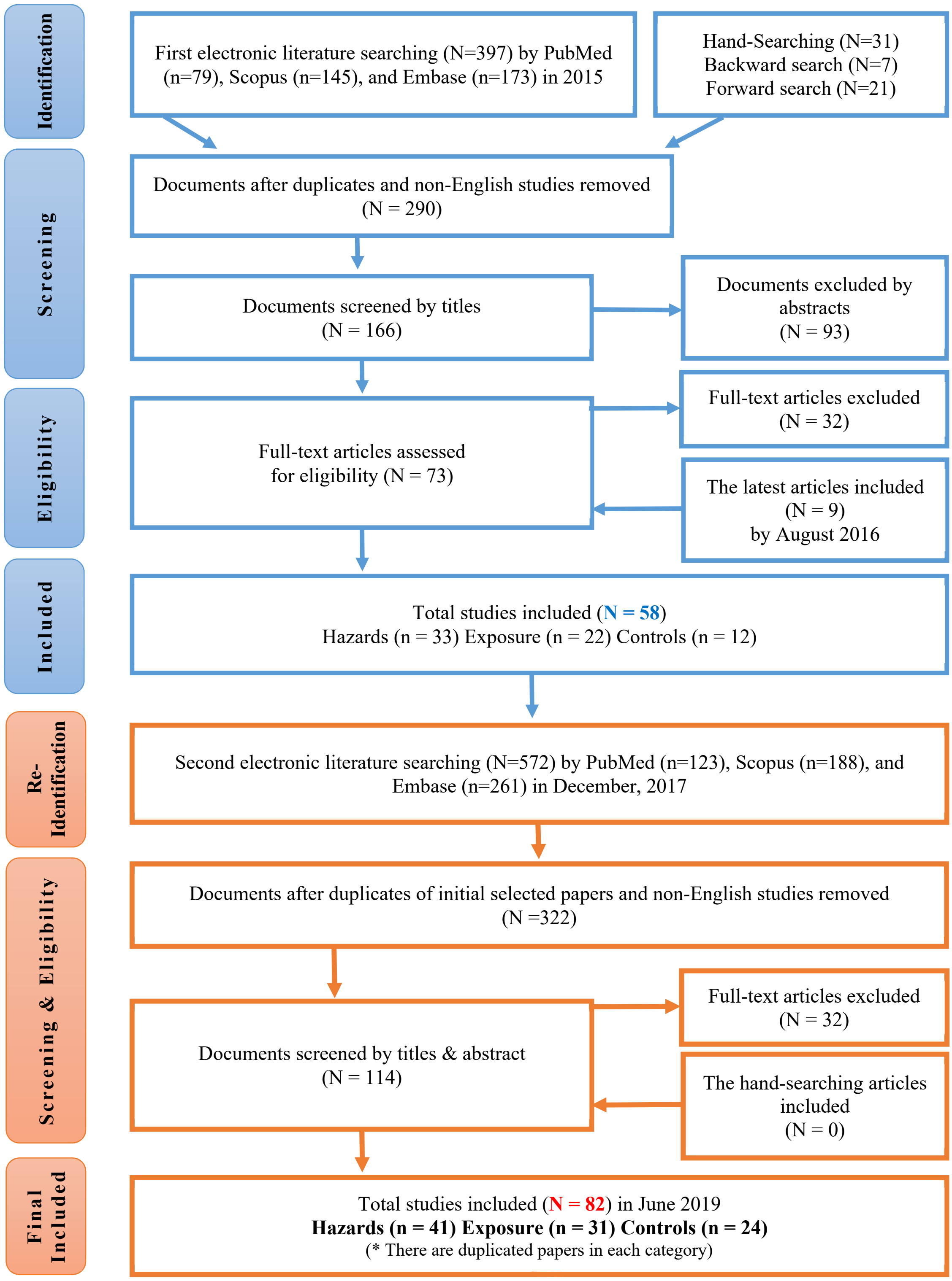

Figure 2.1 Flow Chart of articles' identification by PRISMA 2009

2.4 SUMMARY OF THE LITERATURE (LITERATURE TABLES IN TERMS OF HAZARD/EXPOSURE/CONTROL)

The included documents are summarized in Tables 2.6, 2.7, and 2.8. Tabulated summaries were divided into three categories (Hazard/Exposure/Control).

Classification of the Level of Evidence: To assess risk of bias of the searched evidence for retinal damage of blue light, two different critical appraisal tools were used for the classification of the level/quality of the articles. The tools are the Systematic Review Centre for Laboratory Animal Experimentation (SYRCLE) (Hooijmans et al., 2014) for animal studies and Joanna Briggs Institute (JBI) critical appraisal tools for others (The Joanna Briggs Institute, 2014). Most searched documents were evaluated by classifying into three levels of quality (High, Medium, and Low) (Table 2.5). There are many kinds of critical appraisal tools in the JBI but the assessment of animal studies was conducted using the SYRCLE tool that was created to evaluate the systematic reviews through animal studies.

Table 2.5 Classification of the quality of articles

Critical appraisal tools	High	Medium	Low
SYRCLE tools (total 10 questions)	10 - 7	6-4	3-0
JBI critical appraisal for systematic review studies (Total 10 questions)	10 - 7	6-4	3-0
JBI critical appraisal for Case-Control studies (Total 10 questions)	10 - 7	6-4	3-0

Table 2.6 Summary of key relevant papers – Hazard

Study type	Citation	Quality	Study design	Main findings
Systematic review	Modenese, A., & Gobba, F. (2019). Macular degeneration and occupational risk factors: a systematic review. *International Archives of Occupational and Environmental Health, 92*(1), 1-11.	High CASP (9/9)	• 13 studies included in qualitative synthesis in MD risks of workers • Use of the Newcastle–Ottawa Scale (NOS) for assessing the quality of the studies	Outdoor and blue collar workers exposed to long-term solar radiation are more at risk of MD than those who are not.
Population-based study	Bressler, N. M., Bressler, S. B., West, S. K., Fine, S. L., & Taylor, H. R. (1989). The grading and prevalence of macular degeneration in Chesapeake Bay watermen. *Archives of ophthalmology (Chicago, Ill.: 1960), 107*(6), 847-852.	Medium CASP (5/9)	• 777 watermen in Chesapeake Bay	Sun exposure can cause MD. The size of drusen in RPE grew with age and the bigger and cumulated drusen and age can cause risk factors of macular degeneration.
Case-Control study	Schick, T., Ersoy, L., Lechanteur, Y. T., Saksens, N. T., Hoyng, C. B., den Hollander, A. I., . . . Fauser, S. (2016). History of Sunlight Exposure is a Risk Factor for Age-Related Macular Degeneration. *Retina (Philadelphia, Pa.), 36*(4), 787-790.	High CASP (8/9)	• 3,701 participants of the European Genetic Database	Sunlight is a risk factor for AMD and Some outdoor workers can be exposed to retinal injury while working and there was a significant correlation between past sunlight exposure and early or late AMD. Protective sunglasses are recommended to reduce and prevent progression of AMD.
	Gagné, A. M., Lévesque, F., Gagné, P., & Hébert, M. (2011). Impact of blue vs red light on retinal response of patients with seasonal affective disorder and healthy controls. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 35*(1), 227-231.	High CASP (9/9)	• 10 patients with SAD • Light sources: blue (420 - 520 nm) and red (600 - 670 nm) lamp • blue and red light exposure for 60 min • Seasonal affective disorder (SAD)	Blue light exposure can affect the responses of rod and cone photoreceptors. The duration of blue light exposure for the SAD therapy needs to be considered.
	Czeisler, C. A., Shanahan, T. L., Klerman, E. B., Martens, H., Brotman, D. J., Emens, J. S., . . . Rizzo Iii, J. F. (1995). Suppression of melatonin secretion in some blind patients by exposure to bright light. *New England Journal of Medicine, 332*(1), 6-11.	High CASP (8/9)	• Case-control study (11 blind participants & 6 normal men) • Health effect: Circadian rhythm • Circadian pacemaker, interview & sleep-disorders questionnaire	This study was conducted to determine that bright light exposure can affect circadian rhythm or melatonin suppression of blind participants who cannot sense any light through their eyes. All normal participants showed a decrease of their plasma melatonin concentrations after bright light exposure, however, the melatonin concentrations of three blind participants was also decreased after the exposure to bright light. Even though people who cannot detect light can be influenced by intense bright light in the secretion of melatonin.

Literature review	Tosini, G., Ferguson, I., & Tsubota, K. (2016). Effects of blue light on the circadian system and eye physiology. *Molecular Vision, 22*, 61-72.	-	• Summarize potential health effects from white LEDs	Using existing experimental animals, human cells and simulation studies, this study indicates that white LEDs can damage retina, especially photoreceptors and RPE cells and induce AMD.
	Stamatacos, C., & Harrison, J. L. (2013). The Possible Ocular Hazards of LED Dental Illumination Applications. *Journal of the Tennessee Dental Association, 93*(2), 25-31.	-	• Light sources: White LED headlamp of dental equipment • Dental clinic	LED dental head lamp with high intense blue light can damage the retina and the guideline for protecting potential eye hazards from LED headlamp was presented.
	Yang, H., & Afshari, N. A. (2014). The yellow intraocular lens and the natural ageing lens. *Current Opinion in Ophthalmology, 25*(1), 40-43.	-	• Blue light filtering IOLs	Light exposure can cause AMD and people with typical IOLs from cataract surgery may be at risk compared to others with their crystalline lens. Blue light filtering IOLs may help protect the people with cataract surgery for removing their crystalline lenses from blue light hazards such as AMD.
	Zak, P. P., & Ostrovsky, M. A. (2012). Potential danger of light emitting diode illumination to the eye, in children and teenagers. *Light and Engineering, 20*(3), 5-8.	-	• Light sources: LED	Young children can be more at risk of retinal damages from intense blue light exposure than adults. White LED can be damaging to the young retina.
	Behar-Cohen, F., Martinsons, C., Vienot, F., Zissis, G., Barlier-Salsi, A., Cesarini, J. P., . . . Attia, D. (2011). Light-emitting diodes (LED) for domestic lighting: any risks for the eye? *Progress in Retinal and Eye Research, 30*(4), 239-257.	-	• Measuring for risk groups according to the exposure time: from Risk Group 0 (no risk) to Risk Group 3 (high risk)	White LEDs damaged human eyes and the level of retinal damage from the exposure to white LEDs was much higher than other artificial light sources. The potential damages from white LED exposure were associated with the risk group 1, 2.
	Hunter, J. J., Morgan, J. I. W., Merigan, W. H., Sliney, D. H., Sparrow, J. R., & Williams, D. R. (2012). The susceptibility of the retina to photochemical damage from visible light. *Progress in Retinal and Eye Research, 31*(1), 28-42.	-	• Health effect: AMD • Focused risk factor: Age & gender	This study was conducted to estimate higher prevalence rate by age and gender among European population. The risk associated with late AMD increase with age but gender is not closely linked to the prevalence of AMD.
	Organisciak, D. T., & Vaughan, D. K. (2010). Retinal light damage: mechanisms and protection. *Progress in Retinal and Eye Research, 29*(2), 113-134.	-	• Susceptibility	People or employees who are exposed to blue light sources for a long time may have the potential risk of retinal damage. Blue light can damage cone photoreceptors (especially S-cones) irreversibly and induce the formation of drusen in the RPE which can cause AMD.

Literature review	Connell, P. P., Keane, P. A., O'Neill, E. C., Altaie, R. W., Loane, E., Neelam, K., . . . Beatty, S. (2009). Risk factors for age-related maculopathy. *Journal of Ophthalmology, 2009*, 360764.	-	• Narrative literature review with epidemiological studies and genetic studies	Intense light exposure can be caused by age-related maculopathy (ARM) and the damage from the exposure is cumulative. The relationship between cataract surgery and AMD and genetic factor of AMD are still considered and further clinical studies were suggested.
	Algvere, P. V., Marshall, J., & Seregard, S. (2006). Age-related maculopathy and the impact of blue light hazard. *Acta Ophthalmologica Scandinavica, 84*(1), 4-15..	-	• Evidence-based summary of blue light hazard	Age-related maculopathy can be caused by increasing oxidative stress, cumulating lipofuscin and drusen in RPE and damaging photoreceptor cells. Blue light can also promote these risk factors.
	Nilsson, S. E. G., Sundelin, S. P., Wihlmark, U., & Brunk, U. T. (2003). Aging of cultured retinal pigment epithelial cells: Oxidative reactions, lipofuscin formation and blue light damage. *Documenta Ophthalmologica, 106*(1), 13-16.	-	• Experimental review study • rabbit, albinotic and bovine RPE cells & photoreceptor outer segments • 450 - 500 nm blue light • Measure oxidative reactions & lipofuscin formation	Through authors' previous experimental results regarding increasing oxidative stress, accumulating lipofuscin (LF) in damaged RPE cells from blue light exposure, including photoreceptors damage, this study reported that age-related retinal diseases can be induced by blue light exposure. As the oxidative reaction increases, the LF formation was more built up. Thus, accumulated LF can be the cause for AMD to worsen further. The antioxidant nutrients, such as antioxidants α-tocopherol, lycopene, zeaxanthin and lutein, can contribute to reduce LF formation.
Experimental research (animal/cell studies)	Serezhnikova, N. B., Pogodina, L. S., Lipina, T. V., Trofimova, N. N., Gurieva, T. S., & Zak, P. P. (2017). Age-related adaptive responses of mitochondria of the retinal pigment epithelium to the everyday blue LED lighting. [journal article]. *Doklady Biological Sciences, 475*(1), 141-143.	High SYRCLE (10/10)	• Animal, Case-control • Coturnix japonica (3 age groups_15, 35 weeks) • Light sources: 440 - 460 nm blue LED (Case) & 200 lx standard white glow lamp (Control)	The RPE cells of blue light exposed group showed 1.5 times higher metabolic activity and more mitochondria than control group (non-exposed). Thus, this study presents that blue light exposure can cause the accumulation of lipofuscin granules which can aggravate AMD. They concluded that an increase of mitochondrial activation in the RPE cells can protect photobiological damage caused by the accumulation of lipofuscin.
	Lin, C. H., Wu, M. R., Li, C. H., Cheng, H. W., Huang, S. H., Tsai, C. H., . . . Cheng, Y. W. (2017b). Periodic exposure to smartphone-mimic low-luminance blue light induces retina damage through Bcl-2/BAX-dependent apoptosis. *Toxicological Sciences, 157*(1), 196-210.	High SYRCLE (10/10)	• in vitro & in vivo • human RPE cell & rat retina • Light sources: blue (460 nm) & red (620 nm) LEDs, 80 lx) • Exposure duration: 0 – 48 h for human RPE cells & for 28 days for rat model	RPE cell damages depending on exposure duration in vitro and in vivo were measured. Periodic blue light with low intensity (460 nm, 80 lux) can affect the accumulation of Bax and Bcl-2 and caspase activation in RPE cells. Thus, periodic blue light exposure can damage fundus of the eye, reduce retinal thickness, cause atrophy of photoreceptors and damage retinal neuron transduction.
	Jaadane, I., Villalpando Rodriguez, G. E., Boulenguez, P., Chahory, S., Carre, S., Savoldelli, M., . . . Torriglia, A. (2017). Effects of white light-emitting diode (LED) exposure on retinal pigment epithelium in vivo. *Journal of Cellular and Molecular Medicine, 21*(12), 3453-3466.	High SYRCLE (10/10)	• in vivo) • Wistar rats' RPEs • 10 white LED lamps (2680 cd/m^2, 8.33 W/m^2/sr) & White fluorescent bulbs (2000 lx, 4.14 J/cm^2) • Exposure duration: 4.75, 6, 12, 18 and 24 h	White LED increases oxidative stress in the RPE cells and can affect the autophagy and necrosis of the RPE cells which can be the risk factor of AMD.

Experimental research (animal/cell studies)	Kim, G. H., Kim, H. I., Paik, S. S., Jung, S. W., Kang, S., & Kim, I. B. (2016). Functional and morphological evaluation of blue light-emitting diode-induced retinal degeneration in mice. *Graefe's Archive for Clinical and Experimental Ophthalmology, 254*(4), 705-716.	High SYRCLE (10/10)	• in vivo & in vitro • BALB/c mice • Blue LED (460 nm) • Light intensity: normal to 6000 lx • Exposure duration: 2 h • Equipment: Scotopic electroretinography (ERG)	Using Scotopic ERG, a- and b-waves of mice retinas decreased as exposure time increases. Using electron microscope, there were remarkable decrease of photoreceptors as oxidative stress in RPE cells increases. It can mean blue LED can cause and develop AMD.
	Krigel, A., Berdugo, M., Picard, E., Levy-Boukris, R., Jaadane, I., Jonet, L., . . . Behar-Cohen, F. (2016). Light-induced retinal damage using different light sources, protocols and rat strains reveals LED phototoxicity. *Neuroscience, 339*, 296-307.	High SYRCLE (10/10)	• Animal study • Albino Wistar (W) and pigmented Long Evans (LE) rats • Light sources: LEDs (white, blue, green), CFL, CCFL • Light intensity: 6000 to 500 lx • Exposure duration: 24h	All light sources used in this study induced photoreceptor damage after acute exposure at 6000 lux. The results showed that retinal toxicity can occur in various workplaces from commercial illuminance conditions to high illuminance environments.
	Takayama, K., Kaneko, H., Kataoka, K., Kimoto, R., Hwang, S. J., Ye, F., . . . Terasaki, H. (2016). Nuclear Factor (Erythroid-Derived)-Related Factor 2-Associated Retinal Pigment Epithelial Cell Protection under Blue Light-Induced Oxidative Stress. *Oxidative Medicine and Cellular Longevity, 2016*.	High SYRCLE (10/10)	• human RPE cell • Light sources: LED (450 nm, 1200 lx)	Retinal cell death and ROS generation in RPE cells can be increased by blue light (BL) exposure and the Nuclear Factor (Erythroid-Derived)-Related Factor 2 (Nrf2) can reduce oxidative stress on BL exposure. This study presents that Nrf2 can be one factor for protecting blue light hazards.
	Geiger, P., Barben, M., Grimm, C., & Samardzija, M. (2015). Blue light-induced retinal lesions, intraretinal vascular leakage and edema formation in the all-cone mouse retina. *Cell Death and Disease, 6*(11).	High SYRCLE (10/10)	• Animal study, case-control • double-mutant mice (case) & wild-type mice (control) • For 10 – 30 min blue light expose on the cornea (410 ± 10 nm; 60 mW/cm^2) • After blue light damage, observe strains in retina for up to 10 days	This study is about the damage and death of cone photoreceptors caused by macular degeneration. Blue light can induce the cone photoreceptor death and cone degeneration can be caused by blue light exposure duration, intensity and wavelengths. The results can have important meaning as a monkey has very similar S-cones in the retina to human's S-cones.
	Chalam, K. V., Li, W., Koushan, K., Grover, S., & Balaiya, S. (2015). Effect of distance and duration of illumination on retinal ganglion cells exposed to varying concentrations of brilliant blue green. *Journal of Clinical Medicine Research, 7*(7), 517-524.	-	• RGC-5 (in vitro) • metal halide focal light sources without filters • 1 & 2.5 cm distances • 1, 5 and 15 min exposure durations • Equipment: Light meter	This study measured illuminance levels of metal halide light sources used in vitrectomy surgery that can damage RGCs and suggest the exposure duration for the surgery is within 5 min.
	Jaadane, I., Boulenguez, P., Chahory, S., Carre, S., Savoldelli, M., Jonet, L., . . . Torriglia, A. (2015). Retinal damage induced by commercial light emitting diodes (LEDs). *Free Radical Biology and Medicine, 84*, 373-384.	High SYRCLE (9/10)	• Case-control • Rats' retina (In vitro) • Light sources: LEDs • 6 to 72 h exposure	LEDs including intense blue light wavelengths can damage the photoreceptor cells strongly. The damage can vary depending on different wavelengths

Experimental research (animal/cell studies)	Zhang, P., Huang, C., Wang, W., & Wang, M. (2015). Early changes in staurosporine-induced differentiated RGC-5 cells indicate cellular injury response to nonlethal blue light exposure. *Photochemical & Photobiological Sciences,14*(6), 1093-1099.	High SYRCLE (9/10)	• Case-control • Bovine and rabbit cells (In vitro) • Light sources: blue LED • 3.5, 34.7, and 173.6 min exposure	Low doses (10 J/cm^2) of blue light can damage the retina cells (ROS and mitochondrial contents in ssdRGC-5 cells were produced after 10 J/cm^2 blue light exposure)
	Balaiya, S., Koushan, K., McLauchlan, T., & Chalam, K. V. (2014). Assessment of the effect of distance and duration of illumination on retinal pigment epithelial cells exposed to varying doses of Brilliant Blue Green. *Journal of Ocular Pharmacology and Therapeutics, 30*(8), 625-633.	-	• Case-control • 23 cultured human RPE cells (In vitro) • Light sources: Metal halide focal light source • 1, 5, & 15 min intervals and monitor after 24 h & 72 h • Ophthalmology operation	The longer duration and shorter distance of blue light exposure are correlated with induced retina cell toxicity and the safe exposure time for vitreoretinal surgery is up to 5 min.
	Huang, C., Zhang, P., Wang, W., Xu, Y., Wang, M., Chen, X., & Dong, X. (2014). Long-term blue light exposure induces RGC-5 cell death in vitro: involvement of mitochondria-dependent apoptosis, oxidative stress, and MAPK signaling pathways. *Apoptosis, 19*(6), 922-932.	-	• Case-control • Rats' retina (In vitro_RGC-5 cells) • Light sources: blue LED (main: 464 nm, peak: 456 nm) • 0 to 24 h exposure	Blue light exposure duration has very significant effect on the growth of ROS and protein in the ganglion cell and can impair its own function to deliver the signals from the photoreceptor cells to the brain.
	Kuse, Y., Ogawa, K., Tsuruma, K., Shimazawa, M., & Hara, H. (2014). Damage of photoreceptor-derived cells in culture induced by light emitting diode-derived blue light. *Scientific Reports, 4*, 5223.	-	• Case-control • Murine photoreceptor cells (In vitro) • Light sources: blue (464 nm), white (456 & 553 nm) and green (522 nm) LEDs • 24 h exposure	Blue and white light LED damaged the photoreceptor cells of mice retinas and the cause of damage was the shorter wavelengths of LED.
	Ortín-Martínez, A., Valiente-Soriano, F. J., García-Ayuso, D., Alarcón-Martínez, L., Jiménez-López, M., Bernal-Garro, J. M., . . . Vidal-Sanz, M. (2014). A novel in vivo model of focal light emitting diode-induced cone-photoreceptor phototoxicity: Neuroprotection afforded by brimonidine, BDNF, PEDF or bFGF. *PLoS ONE, 9*(12).	High SYRCLE (8/10)	• Case-control • Case: 7 adult albino rats' right eyes (In vivo_Cone photoreceptors) • Control: rats' left eyes • Light sources: blue LED • 10 sec intervals and monitor during 7 days	Rod- and cone-photoreceptors of rats were damaged by blue light exposure and retinal damage can be prevented with neuroprotective effects such as Brimonidine, brain-derived neurotrophic factor, and pigment epithelium-derived factor.

Experimental research (animal/cell studies)	Shang, Y. M., Wang, G. S., Sliney, D., Yang, C. H., & Lee, L. L. (2014). White light-emitting diodes (LEDs) at domestic lighting levels and retinal injury in a rat model. *Environmental Health Perspectives, 122*(3), 269-276.	High SYRCLE (8/10)	• Case-control • 120 adult male Sprague-Dawley rats • Light sources: blue LED, white LED, and white & yellow CFLs • 12 h/d during 3, 9, or 28 days	Photochemical damage of the retina can be induced by blue-light. Retinal injury from LED exposure was more serious than CFL exposed group.
	Yu, Z. L., Qiu, S., Chen, X. C., Dai, Z. H., Huang, Y. C., Li, Y. N., . . . Gu, H. Y. (2014). Neuroglobin - a potential biological marker of retinal damage induced by LED light. *Neuroscience, 270*, 158-167.	High SYRCLE (10/10)	• Case-control • Sprague-Dawley rats' retina (In vivo) • Light sources: LED (blue 453 nm, green 527 nm, red 625 nm) • 1h and 2h blue light exposure and observed after 1 h exposure	There was no retinal damage for 1 hour of exposure to blue-light, however, after 2 hours of blue-light irradiation, the neuroglobin levels in the retina increased.
	Chamorro, E., Bonnin-Arias, C., Pérez-Carrasco, M. J., De Luna, J. M., Vázquez, D., & Sánchez-Ramos, C. (2013). Effects of light-emitting diode radiations on human retinal pigment epithelial cells in vitro. *Photochemistry and Photobiology, 89*(2), 468-473.	–	• Case-control • Human RPE cells • Light sources: LED (blue 468 nm, green 525 nm, red 616 nm and white) LED • Three light-darkness (12 h/12 h)	Blue and white LED lighting can affect the retinal damage such as the generation of ROS, the damage of DNA or cell death.
	Nakanishi-Ueda, T., Majima, H. J., Watanabe, K., Ueda, T., Indo, H. P., Suenaga, S., . . . Koide, R. (2013). Blue LED light exposure develops intracellular reactive oxygen species, lipid peroxidation, and subsequent cellular injuries in cultured bovine retinal pigment epithelial cells. *Free Radical Research, 47*(10), 774-780.	High SYRCLE (8/10)	• Case-control • Bovine RPE cells (In vitro) • Light sources: blue LED (456 nm) • 1, 10, & 50 J/cm^2 (3.5, 34.7, & 173.6 min) blue-light exposure	The more intense blue-light exposes, the more RPE cells were damaged. The stronger blue light exposure (50 J/cm^2) damaged RPE cell than others.
	Peng, M. L., Lee, C. J., Chien, C. L., Liu, C. L., Tsai, C. Y., Wen, Y. C., & Tseng, K. W. (2013). Protective effects of (-)-epigallocatechin gallate on blue light-induced damage in retinoblastoma Y79 cells by activating estrogen receptor pathway. *Life Science Journal, 10*(1), 192-198.	–	• Case-control • Human Y79 cells (In vitro) • Light sources: LED lamps & white fluorescent lamps • 10 min exposure	Human retina can be damaged by short-term blue light exposure and (-)-epigallocatechin gallate can protect the retinal damage from artificial light sources (especially the short-wavelength visible light).
	Rassaei, M., Thelen, M., Abumuaileq, R., Hescheler, J., Luke, M., & Schneider, T. (2013). Effect of high-intensity irradiation from dental photopolymerization on the isolated and superfused vertebrate retina. *Graefe's Archive for Clinical and Experimental Ophthalmology, 251*(3), 751-762.	High SYRCLE (9/10)	• Case-control • Bovine retina (ex vivo) • Light sources: LED (420 - 480 nm, over 1000 mW/cm^2, dental wireless curing light) • Record light-evoked ERG • 30 cm distances and 45° angles • 5 min single white flash exposure (0.5 s intervals)	High-intensity LED dental curing light damaged the bovine retina and the damage of cone photoreceptors can be exacerbated by the damage of rods. Blue-light filtering device for preventing the eyes should be needed.

Experimental research (animal/cell studies)	Peng, M. L., Tsai, C. Y., Chien, C. L., Hsiao, J. C. J., Huang, S. Y., Lee, C. J., . . . Tseng, K. W. (2012). The influence of low-powered family LED lighting on eyes in mice experimental model. *Life Science Journal, 9*(1), 477-482.	High SYRCLE (10/10)	• Case-control • 40 old mice (In vivo) • Light sources: White LED family lamps (300 - 800 nm) • 2 h/d during 2 - 4 w & 12 h/d during 39 w	It was conducted for investigating the efficacious and safe duration from typical LED light exposure. Typical LED exposure can cause retinal damage (related to photoreceptor loss).
	Knels, L., Valtink, M., Roehlecke, C., Lupp, A., de la Vega, J., Mehner, M., & Funk, R. H. W. (2011). Blue light stress in retinal neuronal (R28) cells is dependent on wavelength range and irradiance. *European Journal of Neuroscience, 34*(4), 548-558.	High SYRCLE (8/10)	• Case-control • R28 rat retinal neuronal cells (In vitro) • Light sources: LED (411, 470 nm) • 15 min, 90 min, 6 h, 24 h, and 48 h exposure	The research conducted to measure levels of irradiance and exposure duration that can damage the retina. The wavelength, 411 nm, was the significant impact in the retina.
	Ueda, T., Nakanishi-Ueda, T., Yasuhara, H., Koide, R., & Dawson, W. W. (2009). Eye damage control by reduced blue illumination. *Experimental Eye Research, 89*(6), 863-868.	High SYRCLE (8/10)	• Case-control • 16 monkeys' retinas with & without blue filters • Light sources: blue LED (465 nm) • 27 - 82 min blue light exposure	Blue filter attenuation can prevent retinal damage from blue light exposure and the more intensity and duration of blue light exposure can induce more retinal damage.
	Dawson, W., Nakanishi-Ueda, T., Armstrong, D., Reitze, D., Samuelson, D., Hope, M., . . . Koide, R. (2001). Local fundus response to blue (LED and laser) and infrared (LED and laser) sources. *Experimental Eye Research, 73*(1), 137-147.	High SYRCLE (8/10)	• Case-control • 27 monkeys' eyes • Light sources: blue and red LED and Laser • 8 - 120 min exposure to blue and red light	Shorter intensive wavelength (blue light) exposures damaged the retina more than longer wavelengths.
	Deprest, J. A., Luks, F. I., Peers, K. H. E., D'Olieslager, J., & Van Ginderdeuren, R. (1999). Natural protective mechanisms against endoscopic white-light injury in the fetal lamb eye. *Obstetrics and Gynecology, 94*(1), 124-127.	Low SYRCLE (2/10)	• Case-control • 16 Fatal Lamb retinas (In vitro) • Light sources: Halogen light source (400 - 700 nm) • 30 min exposure	Light may induce the eye damage caused by exposure time, light intensity, and exposure levels. However, there was no retinal damage in the fetal lamb eye from direct in-vivo light exposure. Eyelid can protect the retinal damage from light exposures.
	Ham, W. T., Jr., Mueller, H. A., & Sliney, D. H. (1976). Retinal sensitivity to damage from short wavelength light. *Nature, 260*(5547), 153-155.	Low SYRCLE (2/10)	• Experimental research • Monkey's eyes • Light sources: various • 1, 16, and 1,000 s exposure	Blue light can induce eye diseases such as cataract and AMD and children and people with aphakic eye should be protected from short wavelengths.
	Noell, W. K., Walker, V. S., Kang, B. S., & Berman, S. (1966). Retinal damage by light in rats. *Investigative Ophthalmology & Visual Science, 5*(5), 450-473.	Medium SYRCLE (4/10)	• Experimental research • Rats' eyes • Light sources: Cool white fluorescent lamps, xenon-mercury compact arc lamp • 10 µsec xenon arc flash stimulated (1 every 2 to 5 min)	Body temperature was associated with the level of the retinal damage from intense light exposure. The peak of light transmission with blue filter was 445 nm. The intense light exposure can damage visual cells and RPE cells irreversibly.

Table 2.7 Summary of key relevant papers – Exposure

Study type	Citation	Study design	Main findings
Workplace Exposure Studies	Pinto, I., Bogi, A., Picciolo, F., Stacchini, N., Buonocore, G., & Bellieni, C. V. (2015). Blue Light and Ultraviolet Radiation Exposure from Infant Phototherapy Equipment. *Journal of Occupational and Environmental Hygiene, 12*(9), 603-610.	• Light sources: 12 different phototherapy equipment items • Work-related: medical personnel • Standard: ICNIRP	The potential risk from UV or blue light of phototherapy equipment depends on the types of lamps. Some light sources from the equipment exceeded the exposure limitation.
	Price, R. B., Labrie, D., Bruzell, E. M., Sliney, D. H., & Strassler, H. E. (2016). The dental curing light: A potential health risk. *Journal of Occupational and Environmental Hygiene, 13*(8), 639-646.	• Five magnification loupes • Light sources: blue-light emitting curing unit (LCU) • Work-related: dental clinician • Standard: ACGIH	Dental clinicians without loupes are at a greater risk for ocular damage from blue LCU exposure than those with loupes. However, loupes increase the amount of irradiance due to magnification of the light on the retina.
	Briggs, T. P., Parker, C., Miller, R. A., Phillips, P. M., Dean, F. M., & Davey, C. C. (1992). Blue Light Emission from Urological Equipment. Can it Damage the Eyes? *British journal of urology, 70*(5), 492-495.	• Light sources: quartz halogen, metal halide, xenon light and cables • Measuring device: spectrometer • Work-related: urologist • Standard: ACGIH	Long term exposure to blue light equipment for therapy may be harmful to the urologists' eye and protective filters for equipment are recommended.
	Roscoe, A. H., & Diffey, B. L. (1994). A preliminary study of blue light on an aircraft flight deck. *Health Physics, 66*(5), 565-567.	• Case study • Measure blue light radiance on the flight deck • Work-related: aircraft • Sunlight exposure • Standard: ACGIH	The permissible spectral radiance of sunlight on the flight deck of aircraft did not exceed the limitation but pilots can be exposed to more intense light than other outdoor workers. The visual field within 2.5 degrees was considered in this study and wearing sunglasses while flight was recommended.
Experimental Simulations	O'Hagan, J. B., Khazova, M., & Price, L. L. (2016). Low-energy light bulbs, computers, tablets and the blue light hazard. *Eye (London, English), 30*(2), 230-233.	• Light sources: CFL, LED, computer screens, tablet computers, laptops, and smartphones • Work-related: public • Standard: ICNIRP	There was no risk on the eyes from low-energy light bulbs exposure.
	Necz, P. P., & Bakos, J. (2014). Photobiological safety of the recently introduced energy efficient household lamps. *International Journal of Occupational Medicine and Environmental Health, 27*(6), 1036-1042.	• Light sources: 19 CFLs, 11 Halogens, 4 LEDs • Measuring device: Spectrometer • Work-related: public • Standard: ICNIRP	The typical household artificial light sources did not exceed the threshold limit values.
	Sliney, D. H., Stack, C., Schnuelle, D., & Parkinson, J. (2014). Optical safety of comparative theater projectors. *Health Physics, 106*(3), 353-364.	• Light sources: arc projector and digital laser-based projector • Work-related: audience in a movie theatre • Standard: ICNIRP/ACGIH	Not significant unless audiences look at the projector directly.
	Dowdy, J. C., & Sayre, R. M. (2013). Photobiological safety evaluation of UV nail lamps. *Photochemistry and Photobiology, 89*(4), 961-967.	• Light sources: 6 UV nail lamps • Measuring the exposure limit • Work-related: nail lamp user • Standard: ANSI/IESNA RP-27.1–05 & 27.3–07	The hazard level on skin and eye from nail lamps was evaluated with a spectroradiometer. The retinal photochemical blue light hazard was not significant.

Experimental Simulation	Mou, T., & Peng, Z. (2013). *Measurement and standardization of eye safety for optical radiation of LED products.* Paper presented at the Proceedings of SPIE - The International Society for Optical Engineering.	• Light sources: LED with illumination of 500 lx • Measuring device: spectrometer • Work-related: non-work • Standard: IEC 60825/ IEC 62471	The optical radiation safety assessment from various light sources can be measured by the retina radiance meter.
	Okuno, T., Ojima, J., & Saito, H. (2010). Blue-light hazard from CO2 arc welding of mild steel. *Annals of Work Exposures and Health, 54*(3), 293-298.	• Light sources: welding torch (CO2 arc welding) • Measuring device: welding robot • Duration of exposure: 120 A to 480 A at intervals 40 A • Work-related: Welder • Standard: ACGIH	Every welder and welding related workers can have serious retinal damage and the protective eye equipment is significantly suggested.
	Liu, J., Zhuang, X. B., Yao, H., & Zhang, S. D. (2014) Methodology for measurement of the blue light hazard of light-emitting diodes with imaging luminance meter. *Vol. 455. Applied Mechanics and Materials* (pp. 460-465).	• Experimental study • Evaluate blue light hazard • spectrometer & luminance meter • Light sources: 24 LEDs & 10 CFLs (CCT: 3000 K to 6000 K) • Standard: CIE & IEC 62471	All CFLs in this study did not exceed the maximum luminance limit, 100 kcd/m^2, but small CFLs with 6500K were close to the upper limit. The luminance from three LEDs with over 6000K exceeded the upper limit. The levels of CCTs were in inverse proportion to the upper limit of luminance. Therefore, the direct emission of LEDs with higher CCTs needs to be blocked to prevent blue light hazard.
	Jou, J. H., Singh, M., Su, Y. T., Liu, S. H., & He, Z. K. (2017). Blue-hazard-free candlelight OLED. *Journal of Visualized Experiments, 2017*(121).	• Experimental study • spectrometer & luminance meter • Calculate the maximum exposure limit of OLEDs • Standard: IEC 62471	A candlelight OLED has 300 times higher power efficiency than candle and showed blue light hazard free than other commercial light sources.
	Bullough, J. D., Bierman, A., & Rea, M. S. (2019). Evaluating the blue-light hazard from solid state lighting. *International Journal of Occupational Safety and Ergonomics, 25*(2), 311-320.	• Literature review & experimental study • Light sources: blue sky, fluorescent, white/blue LEDs, incandescent, sun • 50 cm viewing distances • Work-related: various occupations • Standard: IES & CIE	Illuminances/luminance/permissible exposure times of used light sources were characterised and clear light sources, especially incandescent lamp, showed more potential hazardous than blue/white LEDs.
	Ide, T., Kinugawa, Y., Nobae, Y., Suzuki, T., Tanaka, Y., Toda, I., & Tsubota, K. (2015). LED Light Characteristics for Surgical Shadowless Lamps and Surgical Loupes. *Plastic and Reconstructive Surgery Global Open, 3*(11), e562.	• Light sources: 2 shadowless lamps • 5 clear & coloured eye glasses with surgical loupes • Work-related: microsurgeon • Equipment: spectral irradiance meter	Shadowless lamps in an operating room has over 200 times light intensity than general artificial lamps. In addition, microsurgeon use loupes for surgical precision. Under shadowless lamps, the light energy increased with low-magnification loupes and decreased with high-magnification loupes. Colour filtered eyeglasses should be worn at all times during the operation.
	Chorley, A. C., Baczynska, K. A., Benwell, M. J., W. Evans, B. J., Higlett, M. P., Khazova, M., & O'Hagan, J. B. (2016). Occupational ocular UV exposure in civilian aircrew. *Aerospace Medicine and Human Performance, 87*(1), 32-39.	• Light sources: 1 kW Tungsten Halogen calibration lamp • Work-related: pilots • Record illuminance data every 10 min • Equipment: spectroradiometer • Standard: ICNIRP	Most aircraft can be highly exposed UVA and the windows in the cockpit do not cover the potential eye damage from UV. This study considered the directions of eye movements, 'eye ahead & eye down', and showed 4.5 to 6.5 times excess of UVA limits during flight. There were no potential hazards from UVB exposure during flight.

Experimental Simulation	Kim, H., Kim, H. S., Jung, C. H., & Yoon, I. (2015). A method for reducing blue light hazard from white light-emitting diodes using colourimetric characterization of the display. *International Journal of Control and Automation, 8*(6), 9-18.	• Experimental study • 4 LCD/LED monitors • To characterise colourimetry of displays, standards-related were used • spectrophotometer	This study provides a novel way to reduce blue light hazard from white LED. Use of colorimetric characterization of the display can reduce blue light wavelengths ranged from 400 to 500 nm and especially the peak wavelength (450 nm) was changed by up to 35.9 %. Spectral distributions forms and blue light exposure durations should be considered in further studies.
	Okuno, T., Saito, H., & Ojima, J. (2002). Evaluation of blue-light hazards from various light sources. *Developments in ophthalmology, 35*, 104-112.	• Light sources: various light sources • Measuring device: Spectrometer • Duration of exposure: 8 - 120 min exposure to blue and red light • Work-related: welder • Standard: ACGIH	Evaluation of blue light hazards and measurement of permissible exposure time per day. High-intensity light sources can cause greater retinal damage than low-intensity sources.
	Hietanen, M. T. K., & Hoikkala, M. J. (1990). Ultraviolet radiation and blue light from photofloods in television studios and theaters. *Health Physics, 59*(2), 193-198.	• Light sources: 11 photofloods (metal halide & halogen) • Work-related: photographer/audience • Standard: ACGIH	Photofloods can be damaged to the retina in TV studios and theatres and direct exposure of the light should be limited to a few minutes per day to avoid potential retinal hazards.
	Foster, C. D., Satrom, K. D., & Morris, M. A. (1988). Potential retinal hazards of dental visible-light resin curing units. *Biomedical Sciences Instrumentation, 24*(1), 251-257.	• Light sources: 11 visible-light resin curing units • Work-related: dental clinician • Standard: ACGIH	The study was conducted to measure the permissible exposure for the potential retinal hazards from dental composite resin curing units and the maximum permissible exposure time values (t_{max}) was ranged from 2.4 to 16.4 min daily.
	Moseley, H., Strang, R., & MacDonald, I. (1987). Evaluation of the risk associated with the use of blue light polymerizing sources. *Journal of Dentistry, 15*(1), 12-15.	• Light sources: 4 blue light curing units • Measuring exposure time by ACGIH formula Data measurement time: between 12 and 30 min • Work-related: dental clinician • Standard: ACGIH	The study was conducted to measure the permissible exposure for the potential retinal hazards from dental composite resin curing units and t_{max} ranged from 40 to 100 min daily. Protective eyewear was recommended.
	Satrom, K. D., Morris, M. A., & Crigger, L. P. (1987). Potential Retinal Hazards of Visible-light Photopolymerization Units. *Journal of Dental Research, 66*(3), 731-736.	• Light sources: 11 visible-light photopolymerization units (370 - 730 nm) • Standard: ACGIH	Maximum permissible exposure for the blue light hazards was assessed by ACGIH criteria.
	Okuno, T. (1986). Measurement of blue-light effective radiance of welding arcs. *Industrial Health, 24*(4), 213-226.	• Light sources: 14 different welding conditions • Measuring exposure: 6 seconds • Work-related: welder • Standard: ACGIH	This study was conducted to determine the permissible exposure to blue light for protecting welders' retina hazards by the ACGIH's standard
Other empirical studies	Coleman, A., Fedele, F., Khazova, M., Freeman, P., & Sarkany, R. (2010). A survey of the optical hazards associated with hospital light sources with reference to the Control of Artificial Optical Radiation at Work Regulations 2010. *Journal of Radiological Protection, 30*(3), 469-489.	• Light sources: hospital light sources • Work-related: medical personnel • Standard: ICNIRP	The survey covered examples of office lighting, operating theatre lighting, examination lamps, and sources for ultraviolet phototherapy and visible phototherapies, including photodynamic therapy and neonatal blue-light therapy.

Review Paper	Christensen, T. (2005). Protection against ultraviolet and visible radiation use in medical therapy. *Perinatology, 7*(1), 43-48.	• Light sources: UV and visible radiation sources • Work-related: medical personnel	The survey was compared to the previous hospitals' survey of the medical technical equipment regarding artificial light sources. The values of irradiance from the sources are increasing more than in previous years.
	Behar-Cohen, F., Martinsons, C., Vienot, F., Zissis, G., Barlier-Salsi, A., Cesarini, J. P., . . . Attia, D. (2011). Light-emitting diodes (LED) for domestic lighting: any risks for the eye? *Progress in Retinal and Eye Research, 30*(4), 239-257.	• Literature review • Light sources: natural and artificial light sources • Work-related: medical personnel • Standard: EN 62471	Risk assessment from blue light exposure and classification of risk group about blue light sources according to the EN 62471 are mentioned.
	Lang, D. (2012). *Blue enhanced light sources: Opportunities and risks.* Paper presented at the Proceedings of SPIE - The International Society for Optical Engineering.	• Literature review • Light sources: various artificial light sources • Work-related: public	It shows beneficial effects as well as potential hazards of blue light as a health risk factor. Even though the high blue light sources can damage the retina, blue light hazards can be reduced by indirect lighting.
	European Commission. (2011). *A Non-binding guide to good practice for implementing Directive 2006/25/EC "artificial optical radiation".*	• Guidelines • Various devices indoor workplaces	It shows information of Non-coherent radiation sources, exposure limits and risk assessment in indoor workplaces. Safety classification and hierarchy of control measures for risk management are provided with measurement results of various artificial light sources.
	Sliney, D. H. (1997). Optical radiation safety of medical light sources. *Physics in Medicine & Biology, 42*(5), 981-996.	• Literature review • Light sources: medical UV sources • Work-related: medical personnel • Standard: ACGIH, ICNIRP	Both the health-care worker and the patient, exposed to Optical radiation sources, can damage the retina during the treatment and the surgery due to intense curing lamps.
	Cowan Jr, C. L. (1992). Light hazards in the operating room. [Review]. *Journal of the National Medical Association, 84*(5), 425-429.	• Literature review • Various devices in the operating room • Work-related: medical personnel	Exposures to devices emitting intense light such as operating microscopes, the indirect ophthalmoscopes, and endoilluminators should be limited.
	Jou, J. H., Yu, H. H., Tung, F. C., Chiang, C. H., He, Z. K., & Wei, M. K. (2017). A replacement for incandescent bulbs: high-efficiency blue-hazard free organic light-emitting diodes. [Article]. *Journal of Materials Chemistry C, 5*(1), 176-182.	• Literature review • Light sources: various artificial light sources	This study suggests a more safety and novel organic LED (OLED) which has blue light hazard-free and high energy efficiency than other light sources and similar colour temperature with incandescent lamps and thus, can replace incandescent lamps which are no longer being manufactured in the near future.
	Sliney, D. H. (1997). Optical radiation safety of medical light sources. *Physics in Medicine & Biology, 42*(5), 981-996.	• Literature review • 450 - 500 nm blue light • Standard: IEC 62471, ANSI/IESNA RP27.1-3, ACGIH and ICNIRP	This study introduces lighting standards about CCT, luminance/illuminance, radiance/irradiance and summarized potential risks from blue light exposure using safety-related questions of new types of light sources.

Table 2.8 Summary of key relevant papers – Control (hierarchy of controls)

Hierarchy of Controls	Citation	Quality	Study design	Main findings
Engineering Controls	Kim, H., Kim, H. S., Jung, C. H., & Yoon, I. (2015). A method for reducing blue light hazard from white light-emitting diodes using colourimetric characterization of the display. *International Journal of Control and Automation, 8*(6), 9-18.		• Experimental simulation • Measuring spectral radiances of 4 blue light units	Using colourimetric characterization, blue light emission (peak wavelength: 450 nm) was reduced by up to 36 %.
Administrative Controls	Pinto, I., Bogi, A., Picciolo, F., Stacchini, N., Buonocore, G., & Bellieni, C. V. (2015). Blue Light and Ultraviolet Radiation Exposure from Infant Phototherapy Equipment. *Journal of Occupational and Environmental Hygiene, 12*(9), 603-610.	–	• Light sources: 12 different phototherapy equipment items • Work-related: medical personnel • Standard: ICNIRP	Appropriate safety training for workers exposed to blue light and UV radiation and the specific standard for photobiological safety were recommended. Protective eyewear for newborn babies and workers should be worn to prevent the risk of retinal photochemical hazard.
	Stamatacos, C., & Harrison, J. L. (2013). The Possible Ocular Hazards of LED Dental Illumination Applications. [Article]. *Journal of the Tennessee Dental Association, 93*(2), 25-31.		• Literature review • White LED headlamp of dental equipment • Dental clinic	LED dental head lamp with high intense blue light can damage the retina and the guideline for protecting potential eye hazards from LED headlamp is provided.
	Behar-Cohen, F., Martinsons, C., Vienot, F., Zissis, G., Barlier-Salsi, A., Cesarini, J. P., . . . Attia, D. (2011). Light-emitting diodes (LED) for domestic lighting: any risks for the eye? *Progress in Retinal and Eye Research, 30*(4), 239-257.		• Literature review • Standard: ANSES recommends	ANSES recommendations are reported in accordance with manufacturer and consumer (e.g. common standard of LED products or provision of consumer information avoiding the hazards)
PPE	Li, X., Kelly, D., Nolan, J. M., Dennison, J. L., & Beatty, S. (2017). The evidence informing the surgeon's selection of intraocular lens on the basis of light transmittance properties. *Eye (Basingstoke), 31*(2), 258-272.	High CASP (/)	• Systematic literature review • Grade reviewed 21 studies according to the quality of evidence	Blue light filtering intraocular lenses (IOLs) can be used to minimize the damage of the fovea, associated with central visual acuity, from blue light exposure. However, there were no relevant epidemical studies with the high quality of evidence regarding the more preventive effects of blue filtering IOLs than general UV-only filtering IOLs.
	Hiromoto, K., Kuse, Y., Tsuruma, K., Tadokoro, N., Kaneko, N., Shimazawa, M., & Hara, H. (2016). Colored lenses suppress blue light-emitting diode light-induced damage in photoreceptor-derived cells. *Journal of Biomedical Optics, 21*(3).		• Experimental study (in vitro, case-control) • 661W cells (murine photoreceptor-derived cell line) • Expose to 464 nm blue LED (350 to 800 lx) for 24 h • Various 9 coloured lenses	This study was conducted to exam protective effects of coloured lenses from blue light exposure. The rate of cell death and reactive oxygen species (ROS) production was lower in yellowish coloured lenses than green, pink and antireflective coating lens. In contrast, cell viability was higher in yellowish lenses. The transmittance of blue light differed depending on coloured lenses and it means the protective effect on blue light hazards can be differ depending on coloured lenses.
	Kaido, M., Toda, I., Oobayashi, T., Kawashima, M., Katada, Y., & Tsubota, K. (2016). Reducing short-wavelength blue light in dry eye patients with unstable tear film improves performance on tests of visual acuity. *PLoS ONE, 11*(4).	High CASP (7/9)	• Case-Control study • 22 patients with dry eye	Due to tear instability, patients with dry eye can be more at risk of visual impairment from blue light exposure than normal. Coated glasses for protecting blue wavelengths can be helpful to the patients with dry eye.

PPE	Yang, H., & Afshari, N. A. (2014). The yellow intraocular lens and the natural ageing lens. *Current Opinion in Ophthalmology, 25*(1), 40-43.		• Literature review	Blue light-filtering IOLs can reduce the retinal damage from blue intense short wavelength than typical IOLs. However, these blue filtering IOLs can be inadequate for some patients with night vision difficulty because the IOLs reduce the amount of visible light.
	Rassaei, M., Thelen, M., Abumuaileq, R., Hescheler, J., Luke, M., & Schneider, T. (2013). Effect of high-intensity irradiation from dental photopolymerization on the isolated and superfused vertebrate retina. *Graefe's Archive for Clinical and Experimental Ophthalmology, 251*(3), 751-762.	High SYRCLE (9/10)	• Experimental study (Case-control) • Bovine retina (in vitro) • LED (420 - 480 nm, dental wireless curing light) • 5 min single white flash exposure (0.5 s intervals)	High-intensity LED can damage bovine retina severely. Blue-light filtering device for the eyes should be needed.
	Roberts, J. E. (2011). Ultraviolet radiation as a risk factor for cataract and macular degeneration. *Eye and Contact Lens, 37*(4), 246-249.		• Literature review • Health effect: cataract, MD	Blue light as a short wavelength is a risk factor for Cataract and AMD. The removal of blue wavelengths can reduce the risks and thus, using the wraparound sunglasses or coated contact lenses are recommended.
	Cuthbertson, F. M., Peirson, S. N., Wulff, K., Foster, R. G., & Downes, S. M. (2009). Blue light-filtering intraocular lenses: Review of potential benefits and side effects. *Journal of Cataract and Refractive Surgery, 35*(7), 1281-1297.		• Literature review • Focusing on the patients with cataract surgery or AMD	Blue light-filtering IOLs can reduce the amount of light exposure and protect the retina from the short intense blue light exposure.
	Ueda, T., Nakanishi-Ueda, T., Yasuhara, H., Koide, R., & Dawson, W. W. (2009). Eye damage control by reduced blue illumination. *Experimental Eye Research, 89*(6), 863-868.	High SYRCLE (7/10)	• Experimental study (Case-control) • 16 monkeys' retinas with & without blue filters • blue LED (465 nm) • 27 - 82 min blue light exposure	Blue blocking filtering IOL can attenuate retinal damage from blue-light exposure.

Table 2.9 Summary of key relevant papers – Control (preventions and treatment)

Classification	Citation	Quality	Study design	Main findings
Treatment	Lim, L. S., Mitchell, P., Seddon, J. M., Holz, F. G., & Wong, T. Y. (2012). Age-related macular degeneration. *Lancet, 379*(9827), 1728-1738.		• Literature review • AMD	AMD may be prevented by nutrients (spinach and collard greens), dietary supplements (Vitamins C and E, β-carotene, and zinc), Omega-3 fatty acid supplements and modification of lifestyle factors (smoking, obesity and lack of physical exercise). Laser, photodynamic and anti-VEGF (vascular endothelial growth factor) therapy can be used as the treatment of AMD.
New approach	MacLaren, R. E., & Pearson, R. A. (2007). Stem cell therapy and the retina. *Eye (London, England), 21*(10), 1352-1359.		• Literature review • Stem cell replacement	Retinal stem cell replacement by transplantation is emerging as the new treatment of damaged photoreceptors.
Nutritional supplements	Liang, L., Cui, Z., Lu, C., Hao, Q., & Zheng, Y. (2017). Damage to the macula associated with LED-derived blue laser exposure: A case report. [Article]. *BMC Ophthalmology, 17*(1).		• Case study • 29-year-old man diagnosed macular damage of his right eye from LED derived blue laser • Treated by lutein, multivitamins and ginkgo tablets for four weeks	The right eye of patient with macular damage was treated by prescribed nutritional supplements (e.g. Lutein, multivitamins and ginkgo tablets), but the right eye damaged irreversibly compared to left eye without macular damage. For protecting photoreceptor damage induced by blue LED, bilberry and lingonberry can be used.
	Liu, Y., Liu, M., Zhang, X., Chen, Q., Chen, H., Sun, L., & Liu, G. (2016). Protective Effect of Fucoxanthin Isolated from Laminaria japonica against Visible Light-Induced Retinal Damage Both in Vitro and in Vivo. *Journal of Agricultural and Food Chemistry, 64*(2), 416-424.		• Experimental study • human RPE cell line, ARPE-19 • LED (420 - 800 nm, 3500 lx) • Exposure duration: 12 h	Fucoxanthin can be used to treat retinal damage induced by blue light exposure as well as lutein and zeaxanthin.
	Ogawa, K., Kuse, Y., Tsuruma, K., Kobayashi, S., Shimazawa, M., & Hara, H. (2014). Protective effects of bilberry and lingonberry extracts against blue light-emitting diode light-induced retinal photoreceptor cell damage in vitro. *BMC Complementary and Alternative Medicine, 14*.	–	• Experimental study (Case-control) • Murine photoreceptor cells (661W) • 12 blue LED bulbs (460 - 470 nm) • 6 h blue light exposure and observed after 12 h of the exposure	B-ext, L-ext and NAC from Bilberry and Lingonberry may be beneficial to potential blue LED light-induced photoreceptor damage.
	Ortín-Martínez, A., Valiente-Soriano, F. J., García-Ayuso, D., Alarcón-Martínez, L., Jiménez-López, M., Bernal-Garro, J. M., . . . Vidal-Sanz, M. (2014). A novel in vivo model of focal light emitting diode-induced cone-photoreceptor phototoxicity: Neuroprotection afforded by brimonidine, BDNF, PEDF or bFGF. *PLoS ONE, 9*(12).	High SYRCLE (7/10)	• Experimental study (Case-control) • 7 adult albino rats' right eyes (In vivo_Cone cells) • Control: rats' left eyes • blue LED • 10 sec intervals and monitor during 7 days	Rod and cone-photoreceptor cells can be damaged by blue light exposure and the retinal damage can be prevented with neuroprotective effects such as Brimonidine, brain-derived neurotrophic factor, and pigment epithelium-derived factor.
	Peng, M. L., Lee, C. J., Chien, C. L., Liu, C. L., Tsai, C. Y., Wen, Y. C., & Tseng, K. W. (2013). Protective effects of (-)-epigallocatechin gallate on blue light-induced damage in retinoblastoma Y79 cells by activating estrogen receptor pathway. *Life Science Journal, 10*(1), 192-198.		• Experimental study (Case-control) • Human Y79 cells (In vitro) • LED lamps & white fluorescent lamps • 10 min exposure	Human retina can be damaged by short-term blue light exposure and (-)-epigallocatechin gallate can protect the retinal damage from artificial light sources (especially the short-wavelength visible light).

Nutritional supplements	Roberts, J. E. (2011). Ultraviolet radiation as a risk factor for cataract and macular degeneration. *Eye and Contact Lens, 37*(4), 246-249.		• Literature review	Vitamin E, C, antioxidants (e.g. lutein, zeaxanthin, N-acetyl cysteine) and natural products (e.g. green tea, fruits and vegetables) can be used to protect photooxidative, phototoxic and photochemical damages. However, some nutritional supplements, such as β-carotene or Zn can increase the incidence of some cancers and the balance of supplements should be considered. Wearing wraparound sunglasses and contact lenses are also recommended to prevent retinal damage from UV or short blue light exposure.
	Organisciak, D. T., & Vaughan, D. K. (2010). Retinal light damage: mechanisms and protection. *Progress in Retinal and Eye Research, 29*(2), 113-134.		• Literature review	Natural substances such as extract of ginkgo biloba and synthetic antioxidants such as saffron can prevent retinal photochemical damage.
	Connell, P. P., Keane, P. A., O'Neill, E. C., Altaie, R. W., Loane, E., Neelam, K., . . . Beatty, S. (2009). Risk factors for age-related maculopathy. *Journal of Ophthalmology, 2009*, 360764.		• Literature review with epidemiological studies and genetic studies	Antioxidant status (Vitamin C, D, E and dietary intake) may be protective for ARM or AMD
Other	Zhu, H., Kochevar, I. E., Behlau, I., Zhao, J., Wang, F., Wang, Y., . . . Dai, T. (2017). Antimicrobial blue light therapy for infectious keratitis: Ex vivo and in vivo studies. *Investigative Ophthalmology and Visual Science, 58*(1), 586-593.	High SYRCLE (9/10)	• Experimental study (Animal, Case-control) • Rabbit (ex vivo) & mouse (in vivo) • LED (peak_415 nm)	Antimicrobial blue light (aBL) can be used to treat keratitis. However, aBL therapy can induce retinal photothermal and photochemical damage. Retinal safety should be considered for developing the treatment using aBL.

2.5 APPRAISAL OF THE SELECTED LITERATURE

2.5.1 Hazard

Blue light is emitted from a variety of sources such as sunlight or intense artificial light. It can be also encountered in diverse situations, e.g. medical situations such as dental curing (Stamatacos & Harrison, 2013) or the treatment of neonatal jaundice, (Pinto et al., 2015) and also the performing arts (O'Hagan & Khazova, 2011; Sliney, Stack, Schnuelle, & Parkinson, 2014). The literature refers to significant blue light exposure from white/blue light emitting diodes (LEDs) and metal-halide lamps used in flood lighting or commercial lighting (Okuno, Saito, & Ojima, 2002).

People exposed to environments with different lighting conditions can have different health risks.

Health effects associated with blue light exposure

Blue light wavelengths may affect eyes, skin and influence circadian rhythms (SCENIHR, 2012). Blue light can pass through the outer layer of the skin and thus it is widely used for treatment purposes, e.g. in dentistry or phototherapy for jaundice (Holzman, 2010; Pinto et al., 2015; Price, Labrie, Bruzell, Sliney, & Strassler, 2016; Stamatacos & Harrison, 2013). White bright artificial light sources including these wavelengths are also widely used for treating emotional issues such as Seasonal affective disorder (SAD) (Lurie et al., 2006, as cited in SCENIHR, 2012).

Recent research shows blue light sources for dermatological practice such as acne treatment do not have a significant effect on skin (Skalicky, 2016). Blue light is thought to induce/accelerate age-related maculopathy (Algvere, Marshall, & Seregard, 2006; Lim, Mitchell, Seddon, Holz, & Wong, 2012) and can affect circadian rhythms both positively and negatively (SCENIHR, 2012).

Czeisler and co-workers investigated whether there were subtle changes in the circadian rhythm of eleven blind patients who cannot recognize any light, and found blue light exposure can cause a circadian rhythm disorder, like insomnia (Czeisler et al., 1995). Lockley et al. collected plasma from sixteen healthy subjects with dermal and ocular exposure to both blue and green light. They analysed their melatonin and found that short wavelength at approximately 460 nm monochromatic rays suppressed amounts of melatonin more than longer wavelengths at 555 nm (Lockley, Brainard, & Czeisler, 2003, as cited in SCENIHR, 2012). Human melatonin suppression by light is likely to induce changes in sleep structure. Melatonin production during the night is increased compared with the day but its levels from the exposure to blue short wavelengths is remarkably lower than red light exposure. This result shows blue light can reduce melatonin production (Figueiro & Rea, 2010, as cited in SCENIHR, 2012). On the basis of this information, many researchers believe that blue light causes melatonin suppression and can induce sleep structure, alertness, mood and fatigue (Cajochen et al., 2005, as cited in SCENIHR, 2012; Viola, James, Schlangen, & Dijk, 2008, as cited in SCENIHR, 2012). Besides those, blue light can also increase the incidence of breast cancer in night shift workers, cardiovascular diseases or diabetes (Benhar-Cohen et al., 2011; SCENIHR, 2012).

The major issue from blue light exposure is *irreversible retinal damage* (Algvere, Marshall, & Seregard, 2006; Lin et al., 2017a; Skalicky, 2016; Wu, Seregard, & Algvere, 2006, as cited in SCENIHR, 2012). The theory and observations that blue light can induce retinal damage were first reported by Dufour in 1879. He noted that patients viewing solar eclipse had vision loss by retinal damage (Dufour, 1879). Around 90 years later, Noell et al. reported that intense blue/green light exposure damaged retinal photoreceptor cells permanently through animal testing on rats (Noell, Walker, Kang, & Berman, 1966). The peak wavelength, 441 nm, which can reach the retina and induce retinal photochemical damage, was identified by Ham et al. in 1976 (Ham, Mueller, & Sliney, 1976) and the ACGIH has reported a wavelength of 440 nm amongst the range of blue light as the strongest wavelength that can damage the retinal photoreceptor cells from laboratory studies (ACGIH, 2015).

The potential health effects from exposure to shorter wavelengths of light in electromagnetic radiation are summarized in Table 2.10.

Table 2.10 Potential health effects of shorter wavelengths in electromagnetic radiation (Sources by SCENIHR, 2012)

Potential health effects			Wavelengths /peak	Typical light sources Impact	Work-related Mechanism
Impact	**Mechanism**	**Possible disorder**			
Image forming system (Photoreceptors)	Photochemical damage (Blue light hazard)	Photo-retinitis such as AMD	Blue light (380 - 550 nm) /potential hazardous wavelength: 441 nm	Image forming system (Photoreceptors)	Photochemical damage (Blue light hazard)
	Oxidative stress	Cataract	UVR (100 - 400 nm)		Oxidative stress
Skin	Skin cell damage	Melanoma, skin cancer	UVR (100 - 400 nm)	Skin	Skin cell damage
Overall circadian rhythm disruption	ganglion cell damage from intense exposure	Neuroendocrine effects	Blue light (380 - 550 nm, potential hazardous wavelength: 450 - 470 nm)	Sun, white or blue light sources (e.g. cool white LEDs)	Night shift workers, office workers, medical officials etc.
	Melatonin levels (desynchronization)	Sleep disorder, metabolic syndrome, obesity			
	Melatonin as an antioxidant	Breast, prostate, brain cancers		White light sources (e.g. cool white LEDs or metal halides)	

* e.g. white LEDs, CFLs, metal-halides, arc welding, dental curing lamps, nail lamps, etc.

Phototoxic mechanism of retinal photochemical damage

Human eyes mediate the sense of sight by allowing light (ranging from 400 to 700 nm) to pass through ocular organs such as the cornea, the pupil and the lens, through to the retinal photoreceptors. The cornea generally can block ultraviolet rays less than 295 nm and the lens allows us to avoid risks of retina damage from Ultraviolet-B (UVB) and Ultraviolet-A (UVA) (Algvere, Marshall, & Seregard, 2006; Sliney, 2002). The retina located in the innermost section of the eyeball is the tissue which only exists in mammals and provides excellent visual ability (Hattar et al., 2003, as cited in SCENIHR, 2012). This can detect light by photoreceptors consisting of rod and cone cells and transmit signals to the brain about what the eyes see by photic conversion of rhodopsin (the phototransduction system) (Wu, Seregard, & Algvere, 2006, as cited in SCENIHR, 2012). Blue light can induce damage to retinal ganglion cells (RGCs), photoreceptors as well as retinal pigment epithelium (RPE) via free radical processes coupled to photochemical reactions (Chalam, Li, Koushan, Grover, & Balaiya, 2015; Huang et al., 2014; Kuse, Ogawa, Tsuruma, Shimazawa, & Hara, 2014; Shang, Wang, Sliney, Yang, & Lee, 2014; Zhang, Huang, Wang, & Wang, 2015). For ethical reasons, the evidence of retinal photochemical damage arises from animal studies or in vitro experiments involving cultured human retinal cells.

An initial study showed natural intense light can damage the retina of albino rats and periodic light exposure makes an impact on rhodopsin in the rod cell of albino rats and then, can destroy photoreceptor cells by light exposure duration and intensity and can finally affect vision (Noell, Walker, Kang, & Berman, 1966). Ham et al. measured which blue wavelength can damage the RPE cells and concluded the peak wavelength, that can damage the cells, was 441 nm (Ham, Mueller, & Sliney, 1976). Recently, it was also considered that retinal ganglion cells (RGCs), which are a type of neuron and transmit all information from photoreceptors to the brain, can be damaged by blue wavelengths (Huang, et al., 2014; Zhang, et al., 2015). Drusen accumulated below RPE cells can cause inflammation in the macular especially in the fovea by blue light exposure (Algvere, et al., 2006; Lim, Mitchell, Seddon, Holz, & Wong, 2012). With morphologic changes, increasing apoptosis/viability and merged cells, decreasing mitochondrias, producing reactive oxygen species (ROS) or cumulating lipofuscins and drusen in retinal cells, the photochemical damage can be verified and the damage levels depend on the exposure duration and intensity to the retina (Algvere, Marshall, & Seregard, 2006; Chamorro et al., 2013; Hiromoto et al., 2016; Takayama et al., 2016) (Figure 2.2).

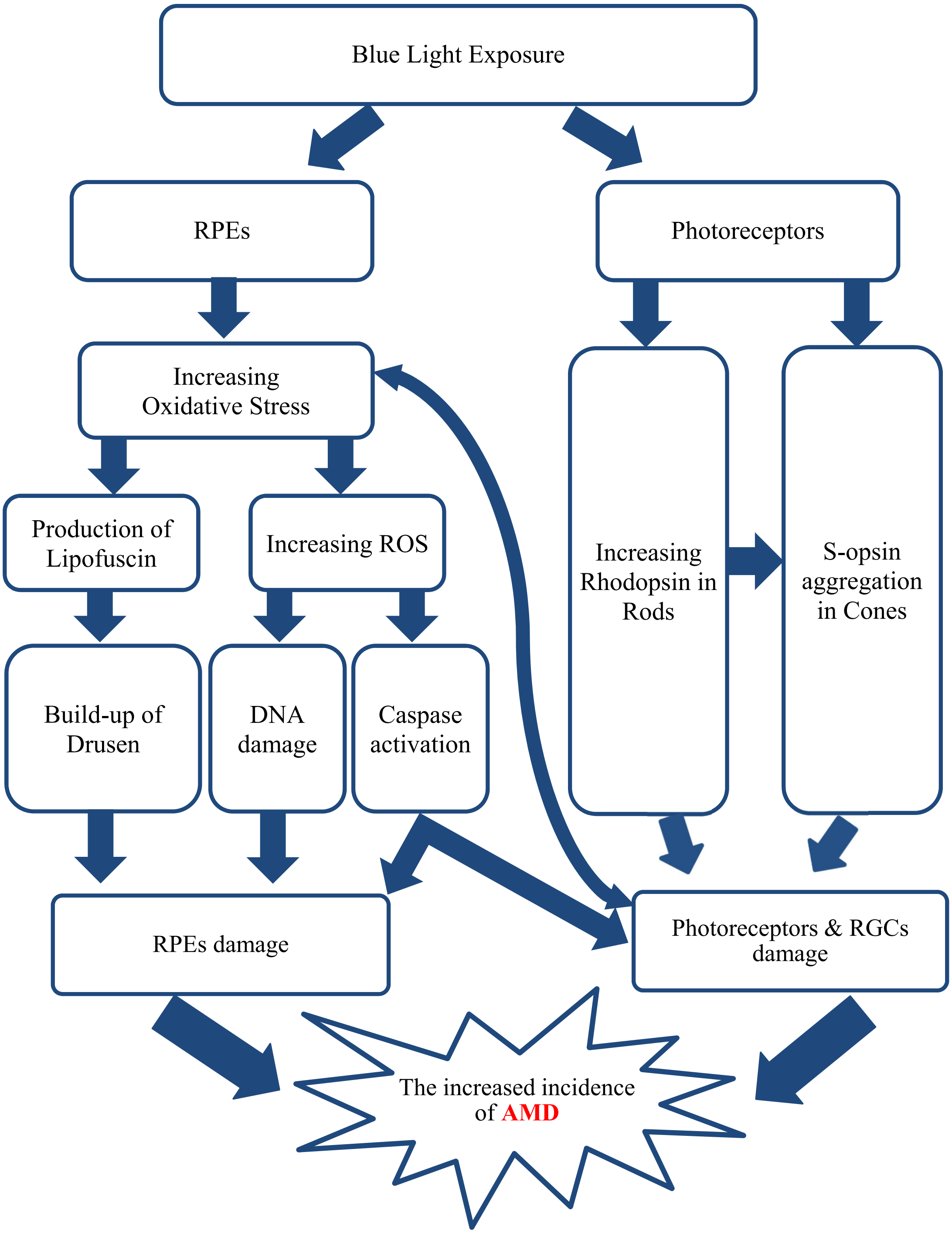

Figure 2.2 The possible phototoxic mechanism of age-related macular degeneration from blue light exposure based on the searched literature (Algvere, Marshall, & Seregard, 2006; Chalam, Li, Koushan, Grover, & Balaiya, 2015; Chamorro et al., 2013; Hiromoto et al., 2016; Kuse, Ogawa, Tsuruma, Shimazawa, & Hara, 2014; Nilsson, Sundelin, Wihlmark & Brunk, 2003; Organisciak & Vaughan, 2010; Takayama et al., 2016).

Significant features of the retinal damage

The damage of photoreceptor, retinal pigment epithelium (RPE) and retinal ganglion cells (RGCs) is correlated with exposure time, frequency and intensity. Noell et al. showed that the more often the cells are exposed to the light, the more photochemical damage occurred (Ham, Mueller, & Sliney, 1976; Noell, Walker, Kang, & Berman, 1966). Lipofuscins in RPE cells build up with advancing years (Algvere, Marshall, & Seregard, 2006; AS/NZS, 2011; Serezhnikova et al., 2017). This is associated with the formation of lysosome and stimulate the production of ROS (Chamorro et al., 2013). Hunter et al. reported that photoreceptor cells were damaged with aging, through experiments with rats, and then reported retinal damage from light exposure was cumulative as time passed (Hunter et al., 2012). The formation of drusen, a significant risk factor for developing age-related macular degeneration, can also be the evidence of the accumulation of retinal damage (Bressler, Bressler, West, Fine, & Taylor, 1989).

The RPE cells may be partially repaired. However, photoreceptors essential for central/peripheral vision are less likely to recover from damage (SCENIHR, 2012). According to experiments with albino rats, there was substantial cone photoreceptor loss through blue LED exposure which did not grow back with time (Ortín-Martínez et al., 2014). RPE cells do not have the function that can recognize light, but can support photoreceptors (Wu, Seregard, & Algvere, 2006, as cited in SCENIHR, 2012) and regenerate through the visual cycle of retinoid metabolism (Organisciak & Vaughan, 2010; SCENIHR, 2012). Among the three blue/red/green cone photoreceptors, blue cone photoreceptors are damaged easily when exposed to blue light and cannot grow back after being destroyed, (SCENIHR, 2012) but green cones can recover from their damage to some extent (Chamorro et al., 2013). It has significant implications to vision whether the damage of photoreceptor cells can be reversible or not. Moreover, it is also necessary to consider the damage of other retinal cells such as RPE cells, RGCs, or bipolar cells which are supporting photoreceptor cells to be able to bring out the best of their functions. Although damaged photoreceptors from the intense blue light exposure cannot regenerate themselves, the cells may be protected from the damage to some degree with natural and synthetic antioxidants (Ortín-Martínez, et al., 2014).

Hunter et al. reported the susceptibility of the retina damaged from intense light exposure in terms of various factors, such as age, AMD, eye diseases, nutrition and nutritional supplements (Hunter et al., 2012).

Generally aging is closely related to retinal photochemical injuries (Wu, Seregard, & Algvere, 2006; Zak & Ostrovsky, 2012). Retinal diseases such as AMD are more common in elderly generation than younger people because the degenerative retinal damage is emerging through long term cumulative light exposure (Wu, Seregard, & Algvere, 2006). Young eyes have more transparent ocular organs than adult ones and 90 % of blue light can pass through the ocular organs and reach the retina (Dillon, Zheng, Merriam, & Gaillard, 2004, as cited in SCENIHR, 2012). Crystalline lens tends to harden and yellow with age. This change may induce eye diseases such as cataracts, however, it can also block more light transmission than the younger lens (Zak & Ostrovsky, 2012). In short, younger eyes exposed to blue light have 20 % increased risk for retinal photochemical damage compared to the eyes of people in their 60s (Dillon, Zheng, Merriam, & Gaillard, 2004, as cited in SCENIHR, 2012). In the same vein, aphakic and pseudophakic eyes may be more exposed to blue light damage than phakic eyes (Algvere, Marshall, & Seregard, 2006). Gender does not appear to be a susceptibility factor in retinal photochemical damage (Noell, Walker, Kang, & Berman, 1966). The prevalence of AMD, the most common retinal disease, is associated with age whereas gender and geographic location are not significant factors (Rudnicka et al., 2012). Patients who have had eye surgery such as lentectomy or corneal cataract surgery, or who were tested for their eye condition with an ophthalmoscope or slit lamp, are exposed to high intense light sources during their surgeries or check-ups and they are highly susceptible to the damage of photoreceptors from the blue light exposure (Connell et al., 2009; Ide et al., 2015; Wu, et al., 2006). People or employees who are exposed to blue light sources for a long time may have the potential risk of retinal damage (Organisciak & Vaughan, 2010).

Age-related maculopathy (ARM) is a disease that mainly occurs in elderly populations especially over 60 years old (Algvere, Marshall, & Seregard, 2006; Connell et al., 2009; Lim, Mitchell, Seddon, Holz, & Wong, 2012). It can be caused by many potential risk factors such as genetic factors (family history or race) or etiological causes (cardiovascular diseases or chronic diseases) or life habit factors (smoking or drinking alcohol) (Connell, et al., 2009; Lim, et al., 2012). Human eyes are exposed to diverse light sources during one's lifetime and as people age, its continuous exposure has accumulated the damage in the retina. Age-related macular degeneration (AMD), the most common retinal damage and the late stage of ARM, can be developed when the retina is continuously exposed to blue intense wavelengths ranging from 400 to 500 nm (Dillon, Zheng, Merriam, & Gaillard, 2004). AMD, particularly late AMD, is an irreparable disease, even though there is the treatment, the effects are limited (Liang & Godley, 2003). Long term blue light exposure can damage photoreceptor cells, RPE cells and RGCs and the damages are accumulated over time and finally induce AMD (Balaiya, Koushan, McLauchlan, & Chalam, 2014; Briggs et al., 1992; Huang et al., 2014). There are several epidemiological studies that visible short wavelengths from sun light may induce the development of ARM and people who are exposed to more visible blue light tend to be at greater risk of ARM. (Bressler, Bressler, West, Fine, & Taylor, 1989; Schick et al., 2016). Figure 2.2 shows the pathway of AMD through the experiment papers cited above. In addition, there is another perspective that ARM can occur by inflammatory response with cumulated drusen between RPE cells and Bruch's membrane (AS/NZ IEC 62471, 2011; Connell, et al., 2009; Organisciak & Vaughan, 2010; Serezhnikova et al., 2017). Wang et al. conducted a cohort study with participants (over 49 years old) for 10 years and reported that patients with early ARM showed signs of the incidence of late ARM with accumulation and size change of drusen (Wang et al., 2007). There are also in vitro studies comparing human normal retinal cells and retinal cells with AMD that demonstrate that cumulative drusen is closely related to AMD (Balaiya, et al., 2014; Huang, et al., 2014; Jaadane et al., 2015; Knels et al., 2011; Kuse, Ogawa, Tsuruma, Shimazawa, & Hara, 2014; Lin et al., 2017; Nakanishi-Ueda et al., 2013; Peng et al., 2013). Several studies regarding sunlight and AMD state outdoor work under sunlight exposure can induce AMD (Bressler, et al., 1989; Schick, et al., 2016), however, there are few or no epidemiological outcomes related to AMD from artificial blue light exposure in terms of occupational health.

2.5.2 Occupational Exposure

Blue light sources

There are a wide variety of blue-rich lamps made for specific purposes in industry, medicine and the arts, and also situations where blue light is a product of industrial processes such as arc welding. (Briggs et al., 1992; Okuno, Ojima, & Saito, 2010; Pinto et al., 2015; Sliney, Stack, Schnuelle, & Parkinson, 2014). For the purposes of this thesis, only incoherent light is considered.

Exposure guidelines and risk assessment approaches

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) and American Conference of Governmental Industrial Hygienists (ACGIH) define exposure criteria and exposure limits from blue light sources (ACGIH, 2015; ICNIRP, 2013). The ICNIRP guidelines consider the field of view from blue light exposure with the range of acceptance averaging angles depending on exposure duration (see below). The overall blue light effective radiance (L_B) and the radiance dose (D_B) are designed to protect against acute photochemical-induced photoretinopathy.

The European Agency for Safety and Health at Work provides a risk assessment process to consider the hazards from intense artificial light exposure in the workplace (European Commission, 2011).

Directionality of light exposure

In order to cause retinal damage, the light must impinge on the body/eye at particular angles. This exposure feature is different from many occupational hazards such as noise. Thus, the occupational visual field should be considered in the workplace (Piccoli et al, 2004). In the case of an audience in a theatre with powerful stage lights, Sliney and co-workers argued that there is no significant photochemical damage if an audience does not stare directly at the sources (Sliney, Stack, Schnuelle, & Parkinson, 2014). Even with the head still, there are minor eyeball movement. In order to address this, the ICNIRP guidelines provide acceptance averaging angle (Υ_{ph}) values (from 0.01 to 0.1 radians; 0.6 to 6 degrees) depending on the maximal exposure duration (ICNIRP, 2013). Hietanen and Hoikkala (1990) considered exposure angles (14° for a conical viewing hood and 5° for narrow field of view) in their experiments relating to television studies and theatres. Briggs et al. (1992) experimented with three different scenarios (direct/indirect/reflect) that urologists can be exposed to using urological equipment. Recent papers have also reported on studies assessing direct/indirect viewing and reflected light exposure from phototherapy equipment or dental curing lamps (Pinto et al., 2015; Price, Labrie, Bruzell, Sliney, & Strassler, 2016).

Pinto et al. (2015) measured the exposure to blue light and UV radiation of infant phototherapy equipment for treating jaundice. In their study, realistic closest distances (20-50 cm) between the light sources and workers/beds/newborns and an acceptance angle of 11 mrad based on ICNIRP guidelines were considered in the exposure scenarios. Price et al. (2016) also assessed potential photochemical risks from dental curing lamps at 40 cm measurement distances, typical viewing distance in dentistry (Price et al., 2016). Dowdy and Sayre (2013) reported spectral evaluation of nail curing lamps at 20 cm distances for non-general light sources (non-GLS) as the worst case scenario (Dowdy & Sayre, 2013).

2.5.3 Occupational Controls

In Europe, optical radiation sources potentially affecting workers' safety, health and welfare (Leccese, Salvadori, Casini, & Bertozzi, 2012) must be assessed and controlled.

A hierarchy of the controls for preventing the retinal damage from artificial blue light exposure in the workplaces is used. This includes lamp selection, engineering controls, administrative controls and personal protective equipment. Health surveillance and training are also mandated. However, it appears that there are relatively few specific studies of hazard control in the peer reviewed literature.

Prevention

The prevention of the retinal damage from blue light exposure in the workplace can be described using the physical and the biological perspectives. The physical perspective can be explained by the hierarchy of control measures recommended by European Commission (Behar-Cohen et al., 2011; European Commission, 2011). The hierarchy focuses on reducing or managing the hazards within the permissible radiance limit (LEL_B = 100 W/m^{2}sr), using, for example, lamp shields or personal protective eyewear. The other perspective for preventing the damage are nutrients from food (vegetables, fishes), dietary supplements (e.g. lutein, zeaxanthin, vitamins C and E, β-carotene) or the change life pattern of patients with retinal diseases such as AMD as the biological perspective (Connell et al., 2009; Lim, Mitchell, Seddon, Holz, & Wong, 2012; Ogawa et al., 2014; Ortín-Martínez et al., 2014; Peng et al., 2013).

Blue blocking intraocular lens (IOL) can be also suggested for aphakic or pseudophakic patients, who need intraocular lens implantation, to reduce the retinal risk from blue light exposure. However, there are some problems about the blue blocking IOLs, e.g. how much blue light should be blocked? Or people with low vision or vision impairments can complain of their non-clear vision, especially night vision difficulty, due to the yellow blue light filtering IOLs (Yang, 2014).

New approaches

There are several treatment methods for macular degeneration using laser treatment, injection therapy and drug treatment (Donoso, Kim, Frost, Callahan, & Hageman, 2006, as cited in Connell et al., 2009; Lim, et al., 2012). Drug treatment can be divided into the prevention purpose and the treatment purpose. Nutritional supplements including Vitamins, β-carotene, zinc, etc. may help both prevent and treat AMD (Connell, et al., 2009; Lim, et al., 2012; Ogawa, et al., 2014; Ortín-Martínez, et al., 2014; Peng, et al., 2013) and Fucoxanthin in luminaria japonica may treat the retinal damage from intense light exposure (Liu et al., 2016). Recently, various new attempts (e.g. gene therapy, radiation therapy, stem-cell therapy and retinal prostheses) has been made to cure the irreversible retinal damage such as

AMD (Algvere, Marshall, & Seregard, 2006; Donoso, et al., 2006, as cited in Connell et al., 2009; Lim, et al., 2012).

2.6 OVERALL SUMMARY OF THE LITERATURE

There is good evidence that blue light exposure can damage the visual photoreceptors and potentially lead to clinically important macular degeneration. The damage from exposure can be acute, cumulative and irreversible. Workers who are exposed to intense sources such as metal halide or arc lamps are at risk of acute effects. A wider group of workers with chronic exposures to sources such as blue rich LEDs may experience long term effects. However, the literature regarding health effects, epidemiology, exposure assessment and control appears to be scattered, and has not been consolidated for occupational health professionals who advise companies on hazard management.

Blue light hazards have been identified through many animal and in vitro studies. Most of the studies reviewed in this literature review are recent studies suggesting that blue light damages the retinal cells in isolation. These authors have also theorized that blue light exposure can also induce retinal diseases such as AMD. However, there is no conclusive clinical evidence to show that blue light exposure causes AMD (Table 2.6).

More than half of the studies were published in the last six years, suggesting it is an emerging issue. The leading research groups in the area are principally from the United States, Europe and Japan. Workplace exposure studies should involve measurements of light exposure in actual workplaces, taking note of sources, the orientation of workers relative to sources, tasks and durations etc. However, such studies are currently tedious, and there is very limited literature. Experimental simulations are more common and typically measure spectral radiance and/or irradiances of light sources under simulated workplace environments. These studies appear to be the majority of research published in this area (12/22 exposure-related articles), and worker scenarios. They can be described as screening studies. The types of light sources characterized for blue light emissions were mostly blue/white LEDs, compact fluorescent lights, metal-halide lights and welding arcs. The workplace scenarios included nail shops, dental clinics, medical fields and welding (Table 2.7).

The controls for blue light photochemical damage can be classified in terms of an occupational hazard control hierarchy. For the control of the retinal photochemical hazard from blue light exposure, sixteen papers were identified and the majority of papers referred to primary controls and personal protective equipment such as protective glasses (Table 2.8 & 2.9). The European Commission Non-Binding Guide rationalizes controls of potential blue light hazards in the workplace (European Commission, 2011).

2.7 GAP ANALYSIS

It is evident that there are limited occupational exposure and epidemiological studies. This is attributable to the complexity of exposure measurement, and in particular the directionality of exposure. Epidemiological studies are hindered by a lack of objective exposure measurements.

Thus, there is a need for further research on exposure assessment, to cover a wider range of situations and also to simplify blue light exposure assessment.

2.8 GENERAL AIMS AND RESEARCH QUESTIONS

Following the literature review, this exploratory research now aims to conduct empirical case studies for selected work environments and tasks. Measured exposures would be compared with current exposure guidelines.

Means of reducing risks will be proposed. These may potentially be generalised to other situations, using a work-worker-workplace risk factor framework.

General Research questions

- How significant is blue light exposure in the Occupational Visual Field?
  - Is the exposure of selected workers in proximity to known blue light sources sufficient to exceed the current blue light exposure guidelines? (Case study approach)

Chapter 3: Methodological Approaches for Case Studies

Following on from the narrative literature review in Chapter 2, the primary research question relates to understanding exposure to blue light in workplace settings. In order to address this question, a case study approach is adopted and uses the principles of occupational hygiene. The overall objective is to understand how blue light exposure occurs and assess the opportunities to reduce exposure, even without a detailed knowledge of the risk of eye damage.

In the first section of this Chapter the case study scenarios will be identified, and the second section will deal with the techniques for assessment of blue light exposure in the occupational visual field. Appendices A to C are relevant to the methodology and used in support of (as preparatory or complementary work to) the case studies.

3.1 CASE STUDY SELECTION SCENARIOS

There are many possible work environments with significant blue light sources (e.g. jewellery shops, retail stores, laboratories, manufacturing, maintenance etc.). For the purposes of this research, the following selection processes were considered.

3.1.1 Identification of blue light sources in workplaces

The American Conference of Governmental Industrial Hygienists (ACGIH) has indicated the types of blue light sources that may represent a significant risk (ACGIH, 2015). Based on this information, the types of blue light sources in workplaces were classified and studied following several discussions with key informants (e.g. illumination engineer, and lighting suppliers).

3.1.2 Considerations selecting the workers using blue light sources in the workplace

Several occupations, such as lighting maintenance workers, nail technicians, jewellery shop workers, retail shop staff and office workers, were considered at the early stage of the research and were discussed through the preliminary stages. After careful considerations such as convenience, risk (perceived blue light risk), vulnerability and time frame for the observational study, three different types of occupations were chosen.

In the first case study, nail technicians who work close to a blue light source i.e. nail curing lamps emitting UVA and blue light wavelengths, were investigated. The second study was of a video production studio using multiple fixed-position bright light sources in order to assess foreseeable blue light exposure of presenters while recording videos. As the third case study, a hand held dental curing lamp used by dental students was assessed (Table 3.1).

Table 3.1 Selected workplaces for case studies.

Workers being exposed	LED blue light source	Workplace
Nail technicians & customers	Nail curing lamp (UVA LED)	Nail shop
Presenters	LED panels & spotlights (white LED)	Video recording studio
Dental students	Dental curing lamp (Blue LED)	Dental simulation clinic

3.2 COMMON ASSESSMENT PROCESSES FOR CASE STUDIES

The following is a description of the approach used for the three case studies.

3.2.1 Observe selected workplaces

Before assessing the blue light sources in the workplaces, field observations were conducted to recognise potential blue light hazards and obtain initial information related to the blue light exposure in the workplace. All observational studies in this research focused on ways to comprehend the commonality of lighting issues in the workplaces. Three workplaces-selected (see Table 3.1) have different types of blue light sources and the workers were also exposed to different lighting environments. To examine actual blue light exposure and its potential risks in the workplace, observational studies were conducted using a simple checklist including the occupational hygiene processes for identifying the basic observational data such as working environments (e.g. working hours, types of tasks, number of workers, locations, sketches if possible, etc.), types of light sources, durations of use of blue light sources and personal protective equipment (PPE) in use. Relevant videos and websites on the internet were also investigated to characterise the diversity of working processes of nail technicians using nail curing lamps, presenters using a video recording studio and dental students using dental curing lamps. All observations in this research were conducted without any interruptions to workers' procedures and there were no ethical issues during the observations.

Through the common observational data, the following information was obtained for the simulation experiments.

- <u>Blue light sources</u>: Blue light sources in the workplace were identified and the duration and frequency of use of the sources were investigated.
- <u>Work activity & Time activity</u>: In order to find out the exposure patterns in the workplace, the data related to types of task, working durations and shifts, working distances to the light source and workers' behaviours were obtained through the observations.
- <u>Eye movements and exposure conditions</u>: To understand workers' occupational visual fields (OVFs), the directions the workers' eyes are focussed on and other

conditions (e.g. distances and angles from worker's eyes to the blue light source) related to the exposure to blue light were observed.

- Create typical/worst case scenarios: Through the observational data, simplified typical and worst case scenarios were created to identify the potential blue light exposure in the workplace.
- Initial assessment of L_{BS}: Effective spectral radiances (L_{BS}) of light sources, used in or related to the selected workplaces, were measured using ICNIRP guidelines (see Table 3.2) and the L_{BS} were used to calculate radiance doses (D_{BS}) using the time activity patterns and working information from the observations.

Creating simplified exposure scenarios

There are many variables in lighting assessments to predict the result accurately. For this, simplified exposure scenarios were needed to build simulation experiments for evaluating exposure to blue light sources in the selected workplace.

Using actual field observational information (e.g. working durations, frequencies/angles/distances of use, etc.), typical- and worst-case scenarios were created and the OVFs considered eye/head movements were determined to conduct simulation experiments.

The exposure case scenarios created from observational studies are detailed in each of the case studies (Chapters 4 to 6).

Performing simulation experiments

The information obtained from field observations in the selected workplaces were used in conjunction with a series of laboratory experiments that simulated exposure. The major perspective of the exposure assessment in the workplace was the determination of the OVFs for the workers.

Custom-made focussing and recording of blue light were used to record the data which were compared to the exposure guidelines e.g. ICNIRP guidelines.

The simulation experiments were conducted in the Lighting Laboratory at the Thebarton campus, the University of Adelaide Video Recording Studio and the Dental Simulation Clinic at the North Terrace campus of the University of Adelaide.

Table 3.2 Emission characteristics of nail curing lamps, LED panels and spotlights and a dental curing lamp

Classification	**Case study 1**		**Case study 2**		**Case study 3**
Work	Nail curing		Video recording		Dental composite resins
Worker	Nail technicians (& customers)		Academies (presenters)		Dental student
Workplace	Nail shops		Video recording studio		Dental simulation clinic
Blue light sources	Gelish 18G 36W nail curing lamp 	Gelish 5-45 18W nail curing lamp 	LEDGO LED panels 	LEDGO Spotlight (LED Fresnel light) 	BA Optima 10 LED dental curing light 
Luminance (cd/m^2)	147	198	13550	231800	11060
CCT (K)	-	-	5924	5591	-
Peak wavelength (nm)	404	405	455	455	456
Blue-weighted radiance L_B (W/m^2sr)	**49**	**60**	**11**	**176**	**192**

3.2.2 Simulation experiments

In order to assess potential workers' exposure to blue light sources in their workplaces, three methodological approaches in the occupational framework (**R**ecognition, **E**valuation and **C**ontrol of the exposure to blue light) were used in the case studies.

For recognising the exposure to blue light, the OVFs of each worker were determined through the observational studies. Based on the ICNIRP guidelines, L_{BS} of blue light sources were measured using a spectroradiometer. Through the results of all studies (literature review and case studies including preliminary and additional experiments), several recommendations for reducing/preventing blue light exposure in the workplace were identified in the case studies (Chapter 4-6) and the part of recommendations (Chapter 8).

Recognition of blue light exposure through preliminary assessment of the selected blue light sources

Based on the kinds of sources of blue light from ACGIH TLVs (Table 1.2), three different types of blue light sources used in the selected workplaces were chosen to assess workers' potential exposure to blue light while working: These were; two LED nail curing lamps (Gelish company, 18G 36W & Gelish 5-45 18W), which are commonly used in nail salons, two types of white LED light sources (LEDGO company, LED panels & LED spotlights) used in the video recording studio, and a type of LED dental curing lamp (BA Optima 10 dental curing light).

Using the spectroradiometer, the selected light sources were evaluated and characterised and the results obtained are given in Table 3.2 and the radiance spectra by wavelengths (nm) of the sources are as shown in Figure 3.1.

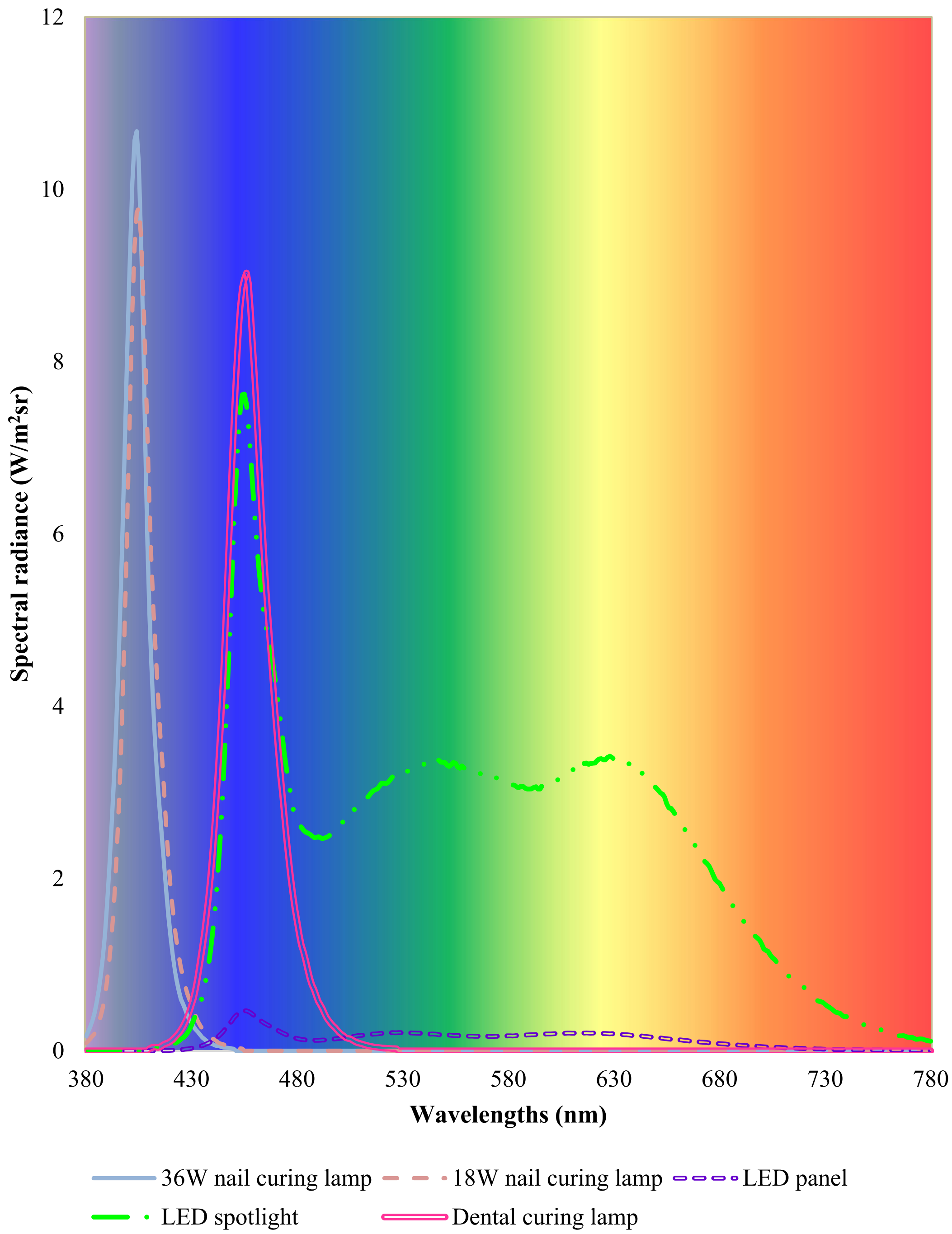

Figure 3.1 Examples of power spectra of the blue light sources measured.

Evaluation of blue light sources

The assessment of the blue light hazard requires the use of a radiometer, or preferably a spectroradiometer, rather than a photometer (lux or luminance meter). The spectral radiance which is the radiant intensity per exposed area is generally used to evaluate the retinal photochemical damage from a light source (Henderson &

Schulmeister, 2004). There is no simple or reliable conversion factor between occupational photometric and radiometric quantities.

The measurement equipment and guidelines used in this research for assessing the radiometric and photometric data of light sources are given below.

Spectroradiometer

A Specbos 1211 UV spectroradiometer (JETI Germany, S/N: 2010143, Calibrated by JETI company) was mainly used to measure spectral radiance/irradiance of light sources in the exposure simulation experiments and was set in the wavelength range from 300 to 700 nm (Figure 3.2). This instrument is a broadband spectroradiometer that can precisely measure the wavelength range from UV (230 nm) to NIR (1000 nm). A filter and a diffusor designed for the Specbos 1211 UV were used to measure the spectral radiance and irradiance of the light sources used in all the case studies.

The data obtained were used to determine whether the potential exposure exceeds the ICNIRP guidelines and to calculate the effective spectral radiances (L_{BS}) and the radiance doses (D_{BS}).

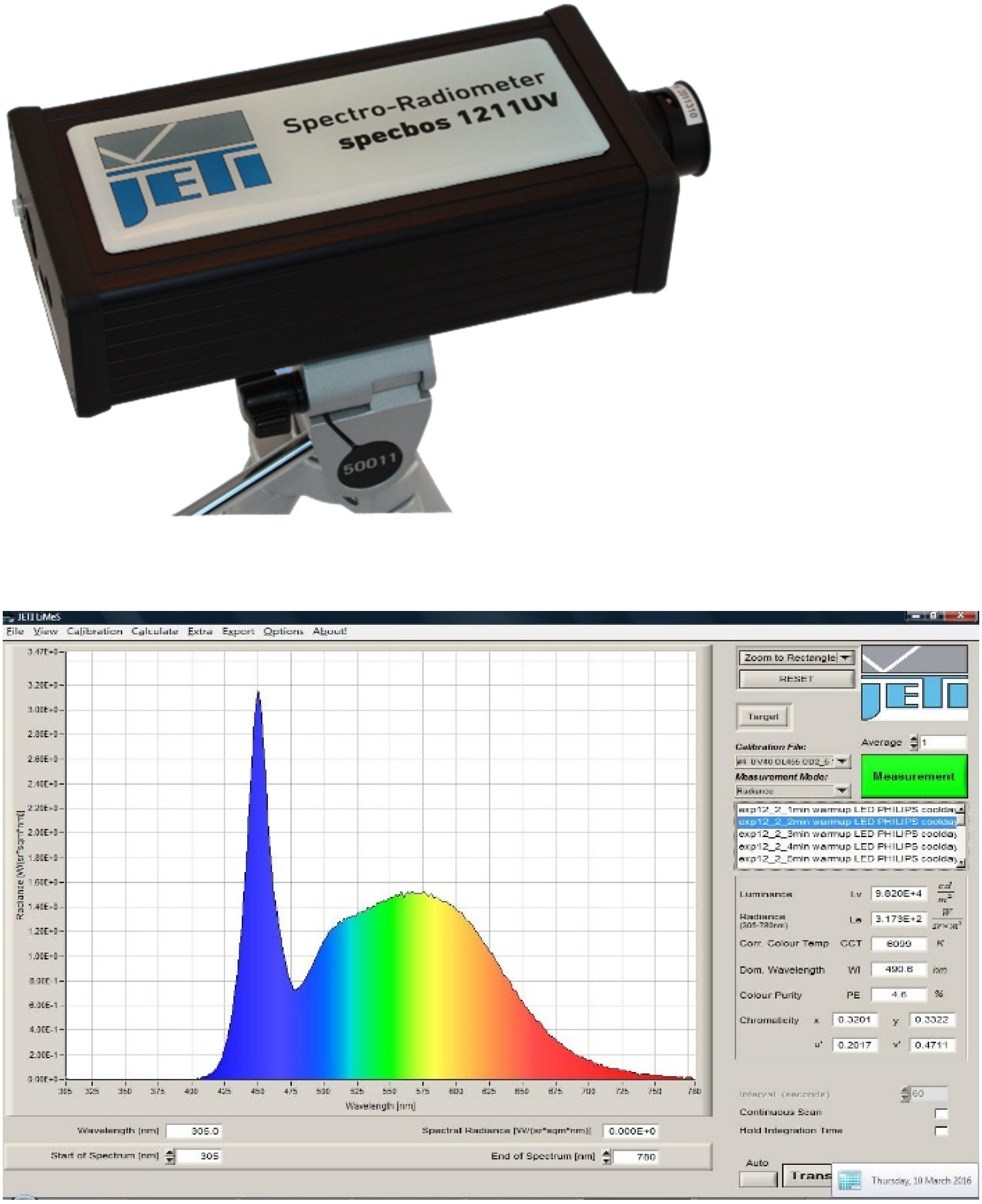

Figure 3.2 The spectroradiometer (top: JETI 1211UV) used for experiments and an example power spectrum (bottom: LiMeS software) of a LED light source

Figure 3.3 Luminance meter (left: Minolta nt-1°) and illuminance meter (right: Digital lux tester)

Luminance meter and Illuminance meter

The Digital Lux Tester (National company, BN-2000LET) and the Minolta nt-1° (Konica Minolta company, S.N: 401626) were used to measure illuminance and luminance of light sources in the experiments respectively and they were calibrated by the QUT photometric Laboratory (Figure 3.3).

ICNIRP guidelines

The equations used from the ICNIRP guidelines applied to all simulation experiments based on field observations and more detailed information about calculation methods of the L_{BS} and D_{BS} mentioned in chapter 4 to 6.

3.2.3 Recommendations from evaluation

The existing control methods for the blue light exposure, e.g. personal protective equipment (PPE) or safety regulations, were investigated and appropriate opportunities for improvement were also identified in the recommendation section.

A series of recommendations were made for stakeholders (e.g. occupational professionals, regulators or manufacturers) as well as recommendations for future research.

3.3 INITIAL EXPERIMENTS AND ADDITIONAL RESEARCH FOR THE ASSESSMENT OF BLUE LIGHT SOURCES (REFER TO APPENDICES A TO C)

A range of initial experiments and supplementary experiments were conducted to develop the experimental techniques. Mobile devices and apps were utilised along with luminance and illuminance meters fitted with a blue filter. These experiments are detailed in the Appendices, and described below.

3.3.1 Preliminary experiments assessing blue-weighted spectral radiances for some common light sources (Appendix A1)

Before carrying out the actual case studies, a range of sources were investigated, including single and multiple LEDs. Spectral distributions, luminance and radiances were characterised. Variability in radiance according to acceptance angle was explored.

3.3.2 Usefulness of luminance meter with a blue filter for identifying blue light sources (Appendix A2)

Based on Okuno's study (1988), the levels of blue-weighted luminance were measured using a luminance meter with a blue filter (HOYA company, glass type: B440, 50×50 mm). Using an RGB colour changing LED globe with 16 different colours and general artificial light sources, luminance and blue-weighted luminance were compared.

3.3.3 Use of mobile phones for workplace lighting environment assessment (Appendix B)

With the remarkable growth in the mobile phone industry, many different kinds of smartphone applications have been created making use of the light sensors, and camera features. Some mobile phone applications can potentially be used for initial lighting surveys in occupational settings.

Google Street View (3D) for a preliminary light survey **(Appendix B1)**

Google Street View (GSV) is the navigation service that provides actual street scenes that can be displayed on mobile phones and IT devices. Users of the software can effectively take panoramic images using their mobiles and upload them in their individual online account. With virtual 3D data from GSV, occupational hygienists can record detailed information about the light environment of workplaces.

Experiments were conducted to find out if the GSV app could be useful for initial lighting surveys, and was used in Case study 2 (video production studio with multiple light sources).

Comparison of light meter apps with professional lux meter in an office setting **(Appendix B2)**

Smartphone based light meters may be more convenient and cheaper than professional lux meters. In this study, side by side comparisons were undertaken, utilising 8 different mobile devices, with two operating systems and mobile phone applications.

Can a mobile phone be used for blue light assessment: preliminary experiments with a blue filter on mobile phone light sensor? **(Appendix B3)**

A luminance meter can emulate blue-weighted spectral radiance (L_B) if appropriate blue filtering is used and correction factors determined with a spectroradiometer (Okuno 1988). However, use of blue filters on illuminance meters has not been reported in the literature. Using a blue filter (HOYA company, glass type: B440, 50 × 50mm), blue-weighted irradiance using a professional lux meter and with mobile phones were measured.

3.3.4 Attenuation of blue light using eye protection (Appendix C)

This experiment was conducted to determine how much protective safety glasses or sunglasses can reduce the blue weighted spectral radiance (L_B). Using the spectroradiometer, the L_Bs of a clear safety glasses, two blue protective yellowish safety glasses and a red-brown colour sunglass were measured. A dental curing lamp was used as the blue light source and all outcomes were compared and analysed.

Chapter 4: Case Study 1 (Nail curing lamp)

This case study reports on simulated exposures from the use of two commercially available LED nail lamps. Time activity patterns were established by observation in seven nail salons in Adelaide. Worst case and typical situations were considered and simulated. Integrated effective spectral radiances from the nail resin curing lamp in the occupational visual field were recorded with a spectroradiometer, modified with a customised imaging attachment. Key considerations were the initial determination of the OVF, and:

- whether or not blue light is present in a significant region of the field,
- for how long the blue light is present and
- the radiance.

4.1 PURPOSE OF CASE STUDY 1

The aims of the first case study were

(1) to characterise the potential blue light exposure for nail technicians and their customers,

(2) to simulate exposure data in a laboratory using two commercially available LED nail curing lamps commonly used in beauty salons based on real working scenarios and

(3) to compare exposures with ICNIRP guidelines.

4.2 INTRODUCTORY BACKGROUND RELATED TO NAIL TECHNICIANS

Nail curing lamps in manicure and pedicure salons can represent a source of blue light exposure in the workplace. UV nail curing lamps which are designed for nail coating curing processes, emit UV radiation and blue light (Dowdy & Sayre, 2013; Markova & Weinstock, 2013). There are two types of light sources used in UV nail lamps, namely UV fluorescent lamps and LED lamps, and a large number of different types of commercial nail lamps are marketed for nail technicians or general users. LED type curing lamps are increasingly being favoured as they are considered effective and practical.

In the USA, there are an estimated 130,000 nail technicians, and the nail care-related industry is growing continuously (Nails magazine, 2016). There are over 11,200 beauty-related businesses, including beauty salons, in Australia (Maven Marketing, 2016), and the industry is also increasing steadily (Job Outlook, 2017).

In the only study of nail lamps, Dowdy and Sayre (Dowdy & Sayre, 2013) measured different types of commercial nail curing lamps at a distance of 20 cm and at angles of 0° (direct) and 45°. Based on the ICNIRP criteria, the retinal risk of the nail curing lamps was deemed to be low. However, it was found that LED sources in these devices had light emissions two times higher than fluorescent sources (Dowdy & Sayre, 2013). They measured irradiances, rather than radiances, the latter being the most appropriate metric for blue light risk assessment (Henderson & Schulmeister, 2004). Time activity patterns for assessment of dose were not reported.

There are nuances in the ICNIRP blue light exposure guidelines and aspects of practical measurement that are not immediately obvious for those seeking to assess workplace risk according to the guidelines. For one thing, measurements should be conducted in the occupational visual field (OVF) (Piccoli et al, 2004), with special consideration of the averaging angle of acceptance of the retina. According to ICNIRP, the acceptance averaging angle is time dependent (from 0.01 to 0.1 radians or 0.6 to 6 degrees) (ICNIRP, 2013). However, depending on the actual task and worker behaviour, a larger averaging angle can be used, provided that any spot on the retina is not exposed beyond the radiance dose limit. In terms of macular degeneration and maintenance of visual acuity, the key requirement is that this spot is on the macula. Damage to the peripheral retina makes relatively little difference to visual function, as evidenced by laser treatment for diabetic retinopathy (Youssef, Sheibani, & Albert, 2011). This means that the risk should be assessed on any blue light source in the visual field that may be imaged on the macula.

4.3 EXPERIMENTAL METHODS

The workflow of this case study consisted of three steps: Preliminary data collection, field observations and simulation of exposure.

Preliminary data collection

Before the case study 1 began, initial information regarding nail curing lamps and working environments of nail technicians were collected from published literature. Using various media content on the Internet, such as YouTube videos and beauty blogs, tasks of nail technicians (e.g. curing times or frequency of use of nail lamp per one customer) and characteristics of nail lamps (e.g. instructions or precautions) were understood. Information about the types or common characteristics of nail curing lamps were investigated in a retail beauty shop in Adelaide and in the Hair and Beauty training area in TAFE SA in May, 2016.

Seven nail salons, located in Adelaide were then visited from 21 April 2016 to 29 July 2016. During the two months duration for the field observation, the observer(s) received manicures directly or watched the workers' working processes indirectly. All observations were conducted without any interruption and no ethical issues were raised. (Figure 4.1)

The data from the field observations, e.g. the hours and frequency of use of nail lamps, were collected and used in the simulation experiments for characterising time activity patterns using the hours and frequency of use of a nail lamp, and identifying the spatio-temporal relationship between workers, customers and nail lamps, e.g. exposure distances and angles, using working patterns of nail technicians.

Figure 4.1 An example of field observations in one nail salon
(The photo was taken with the permission of the nail technician.)

Instrumentation

A Specbos 1211 UV (JETI Germany, S/N: 2010143) spectroradiometer, with LiMeS software (Version 4.1.0m), was used to measure the spectral radiance of light sources in the laboratory simulation experiments and was set in the wavelength range from 300 to 700 nm at 1 nm intervals.

Nail curing lamps

A 36W LED professional nail curing lamp (Gelish 18G) and an 18W LED training lamp (Gelish 5-45) were used. The 36W lamp had 18 x 2W LEDs in an array and the latter had an 18 x 1W LED array (see Figure 4.2).

Figure 4.2 Nail curing lamps
(Left to right (a) 36W UV curing lamp; (b) 18 W UV curing lamp)

The nail curing lamp emissions were evaluated using the spectroradiometer and characterised in Table 4.1 and the radiance spectrum by wavelength (nm) of the Gelish 18G 36W LED nail curing lamp is as shown in Figure 4.3.

Table 4.1 Emission characteristics of the nail curing lamps

Measuring equipment	Measurement	Nail curing lamp	
		Gelish 18G 36W	Gelish 5-45 18W
Spectroradiometer Specbos 1211UV	Luminance [cd/m^2]	147	198
	Blue-weighted radiance L_B [W/m^{2}sr]	49	60

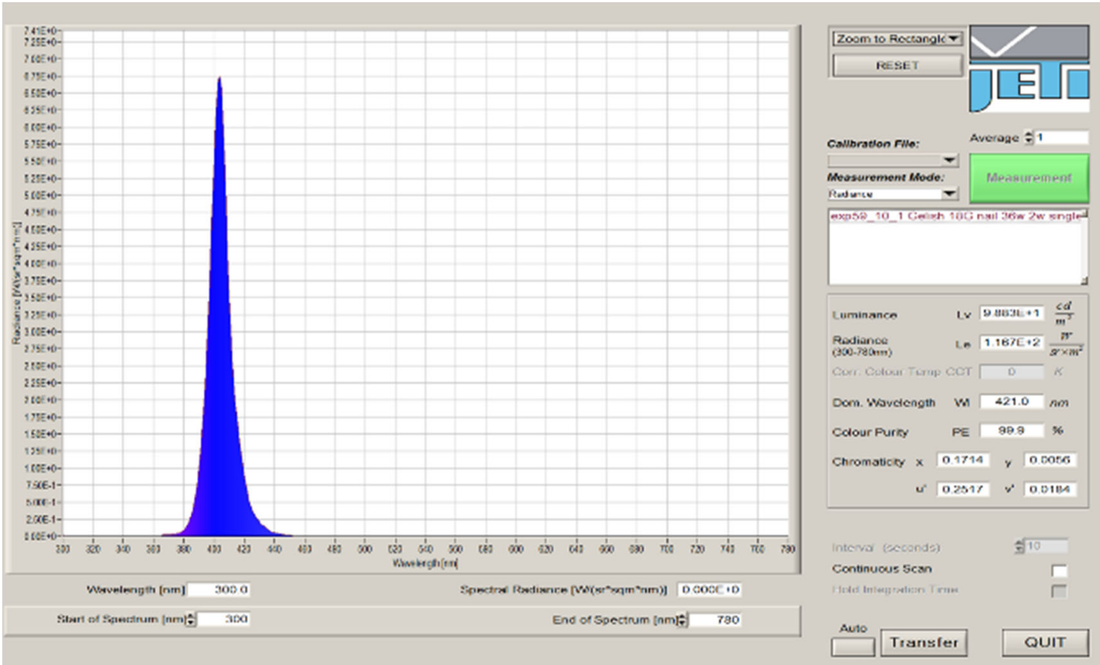

Figure 4.3 An example power spectrum of a Gelish 18G nail curing lamp

Nail curing lamp exposure assessment simulation

Two different case scenarios (typical/worst case) were created, i.e. for a nail technician and a customer.

The simulation experiments with LED nail lamps were conducted as shown in Figure 4.4 with targeted measurements at the centre, right corner and left corner in front of the lamps (Figure 4.5). The lamps' radiance was measured at 30 cm distance and at an angle of 45 degrees (informed from the workplace observations – see below) and measurements were taken when the lamps automatically turned on over 30 sec for a 36W lamp and 45 sec for the 18W lamp (Figure 4.4).

All measurements with LED nail curing lamps were conducted in a dark room and were combined with data regarding work conditions (e.g. exposure durations, distances, angles, working hours) from information gathered in the observational case study in the nail salons.

Computation

Using the equation provided by the ICNIRP guidelines, the effective blue light radiance (L_B) and the effective blue light radiance dose (D_B) were calculated and assessed.

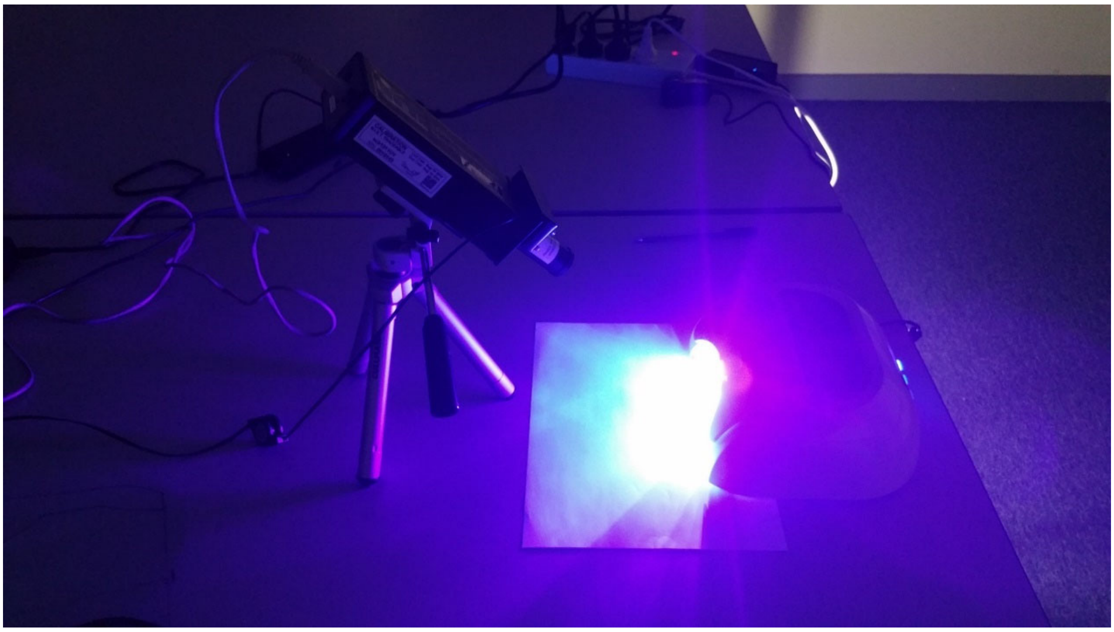

Figure 4.4 Example measurement setup

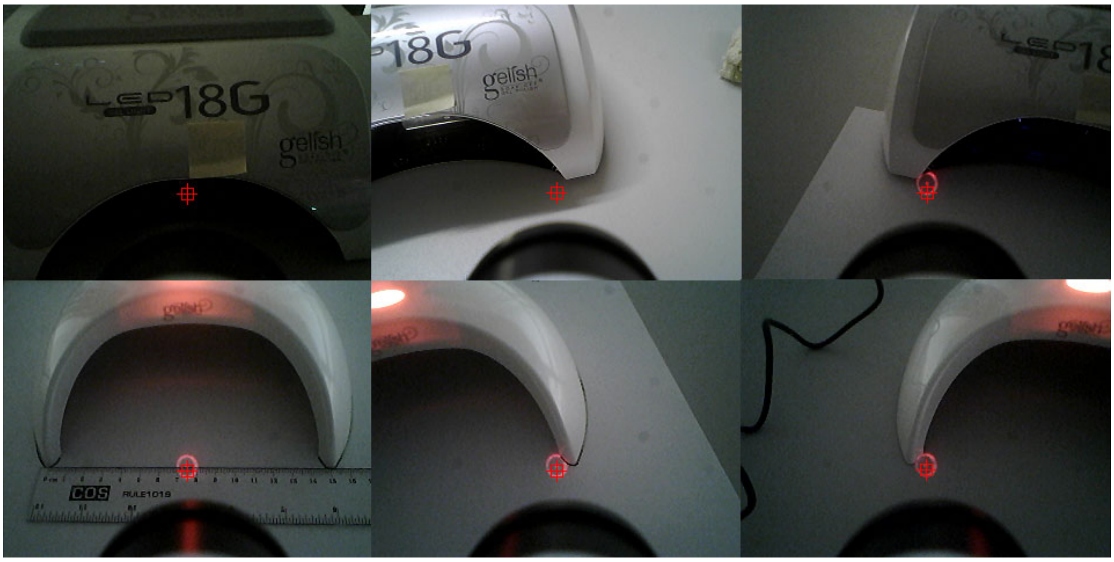

Figure 4.5 Targeting points for the measurements; centre, right corner and left corner

4.4 RESULTS

Field data

In total seven nail salons located in Adelaide (4 salons on weekend, the busiest time, 1 salon in the daytime, and 2 salons in the afternoon, after 5 pm) were visited. Observations were carried out at each salon for average customers, noting the curing times, or environmental conditions for around 30 minutes to 1.5 hours. Most salons were using LED nail curing lamps and there was only one salon using a fluorescent type lamp designed for two hands. From the observations, the average nail curing time was 30 to 45 sec per one nail top coat by a LED nail lamp and the fluorescent lamp was used for over 120 sec. On average, customers have 4 or 5 top coats per hand and it took 20 to 30 minutes for a nail service. Therefore, the average typical curing times were around 300 to 800 sec (Table 4.2). For pedicure services, it takes for around 1 hour and it is longer than for the hand nail services. However, they used essentially the same method with the manicure (e.g. same frequency for the top coat of the manicure). The actual distance between the nail technicians/customers and lamps was around 30 to 40 cm and the nail technicians were usually closer to the lamps than were the customers.

Table 4.2 General information from the observations in seven nail salons

ID. #	Observation	Number of Customers	Curing Time (s)/ Nail lamp	Top Coat Frequency	Average Typical Curing Time* (s)	Type of Nail lamp
Nail salon 1	Daytime†	4	45 s	4	360	LED
Nail salon 2	After 5 pm‡	7	40 s	4	320	LED
Nail salon 3	After 5 pm	6	30 s	5	300	LED
Nail salon 4	Weekend♯	Over 15	40 s	5	400	LED
Nail salon 5	Weekend	Over 15	Over 120 s	4	800	Fluorescent
Nail salon 6	Weekend	Over 10	45 s	4	360	LED
Nail salon 7	Weekend	Over 20	40 s	4	320	LED

* Average typical nail curing time (s) × top coat frequency × 2 hands
† Daytime: Weekdays from 9 am to 5 pm
‡ After 5 pm: Thursday and Friday (busiest shopping days)
♯ Weekend: Saturday and Sunday from 11 am to 5 pm
[The opening hours of all nail salons were from 9:00 am (weekdays) and 11:00 (Sunday & holidays) to 5:00 pm (weekdays) and 9:00 pm (shopping days).]

Some customers also requested special nail art services. In some cases, the customers may be exposed to a nail lamp for a much longer period. Similarly, a nail technician may make custom hand-made false nails for customers and the technician will be exposed to a nail lamp for extended periods. Table 4.2 summarises the observations from the nail salons. Estimated direct blue light viewing times were calculated by actual nail curing frequency and estimated viewing duration for a nail technician and a customer during nail curing. Since the human eye does not normally focus on one spot for any significant period of time, the viewing times of a nail lamp needed to be estimated. Three positions in the opening of the two nail lamps were determined (Figure 4.5) and the viewing duration of each position was estimated to be 3 sec. The estimated exposure durations for a customer and a nail technician are typically 72 sec (1.2 min) and 360 sec (6 min) respectively and for the worst case estimates are 900 s (15 min) for a customer and 2,700 s (45 min) for a technician.

Table 4.3 Estimated direct blue light viewing times for customers and technicians

		Customer	Nail technician
Typical case	Total duration	72 seconds	360 seconds
Worst case	Total duration	900 seconds	2700 seconds

- Calculation for typical case for customer: 9 sec gazing per one checking × 4 times checking × 2 hands = 72 sec
- Calculation for typical case for nail technician: 9 sec gazing per one checking × 4 times checking × 2 hands × 5 customers per day = 360 sec
- Calculation for worst case for customer: 9 sec gazing per one checking × 10 times checking × 10 fingers = 900 sec
- Calculation for worst case for nail technician: 9 sec gazing per one checking × 10 times checking × 10 false nails × 3 customers per day = 2700 sec

The general lighting service lamps (e.g. ceiling/wall lamps or desk lamps) were LEDs and compact fluorescent light bulbs (CFLs) and there appeared to be no significant blue light sources in the salons other than the nail lamps.

Simulation experiments

For the laboratory simulations, four different inside bases (metal reflector, white/grey/black paper) were considered (for reflective properties) and used for measurement, to compare the spectral radiances of the nail lamps. Nail lamps with a metal reflector gave the highest results. The 36W LED nail lamp was designed with a metal reflector and a protective opening cover to limit blue light exposure. The 18W LED had neither a shielding cover nor a metal reflector at the bottom, just a plastic base.

The highest peak emission of both LED nail lamps was at 404 nm. The stronger powered (36W) LED nail lamp showed higher radiances than the low powered (18W) lamp, however, it was noted that the effective blue light radiances from the corner of the opening of the 18W lamp, which has a wider opening, had similar outcomes with the 36W lamp (Table 4.4).

Table 4.4 presents the outcomes from the simulations with the two types of LED nail lamps. Radiances at 45 degrees (estimated normal viewing angle) were measured at various points along the base of the lamp (see Figure 4.4 & 4.5). The effective blue light radiance (L_B) and the effective blue light radiance dose (D_B) were calculated using the data from the spectroradiometer and the estimated viewing times from observations.

The data from Table 4.4 shows that the L_Bs and D_Bs are well below the current limits, even in the worst case. That is, for viewing durations up to 10,000 sec (2.8 hr) the D_B must not exceed 10^6 J/m^2·sr and for periods greater than 10,000 sec, the limit of the L_B is 100 W/m^2·sr (ICNIRP, 2013).

Table 4.4 The effective radiances (L_B) and the daily estimated effective radiance dose (D_B) for nail technicians

Nail lamp	**Target**	**L_B** (W/m^{2}sr)	**D_B** (J/m^{2}sr) Typical case	**D_B** (J/m^{2}sr) Worst case
36W LED nail lamp (2W×18LEDs)	Centre	9.17		
	Right corner	2.26		
	Left corner	6.68		
	Average	**6.04**	2,174	16,308
18W LED nail lamp (1W×18LEDs)	Centre	0.23		
	Right corner	1.96		
	Left corner	6.65		
	Average	**2.95**	1,062	7,965

* The limit of L_B: 100 W/m^{2}sr (exposure time > 10,000 sec/day)and the limit of D_B: 10^6 J/m^{2}sr (within 10,000 sec/day) (ICNIRP, 2013)

The highest L_Bs measured were 60 W/m^{2}sr (18W LED nail lamp) and 81 W/m^{2}sr (36W LED nail lamp). The centre and the edge of the LED units of both nail lamps could not be measured due to the limited measuring range of the Specbos. If a person gazes at the nail lamp for all throughout the curing, the blue light hazards of the worst case scenario will be over 162,000 J/m^{2}sr for 18W nail lamp and 218,700 J/m^{2}sr for 36W nail lamp.

The lower powered 18W LED nail lamp with its designed opening (18W LED nail lamp) generally showed lower levels of the L_B than 36W lamp with an opening cover, however, the corner of the opening of the 18W lamp showed higher L_Bs than other areas-targeted.

4.5 DISCUSSION

Most concerns about UV nail lamps are associated with skin effects from UV exposure. There is only one study that considered the blue light retinal hazard for the eyes. Dowdy and Sayre (2013) measured UV fluorescent and LED nail curing lamps and determined the classification of the risk groups of each nail lamp. They reported that the potential retinal risk was not significant, but they identified LED nail lamps as emitting more blue wavelengths than fluorescent UV nail lamps. Their study was not based on actual field work and used the American National Standards Institute/Illuminating Engineering Society Recommended Practice-27 (ANSI/IESNA RP-27) standard for risk grouping (IESNA Photobiology Committee, 2001). However, only angles of 45 degrees and 0 degree (direct) were considered as part of the actual assessment.

The design of UV nail lamp openings is such that they generally face the actual users and thus customers may have higher exposures than nail technicians during the brief curing process. However, most customers only visit nail salons periodically (e.g. monthly), while nail technicians have many customers to attend to daily. In workplace observations in this research, nail technicians had 20 to 40 min curing times per customer and treated several people during a working day. The nail industry has reported around 60 % of nail technicians in USA offer nail care services to an average of 20 to 45 customers a week (Nails magazine, 2016). Consequently, the duration of workers' exposure to UV nail lamps would greatly exceed that of a typical customer's exposure.

This research is the first to attempt to measure the spectral radiances and the spectral radiance doses in terms of the actual working environment. Interestingly, the corners of the 18W LED nail curing lamp showed higher values of L_B than at the centre. It shows the amount of exposure can differ depending on the position of the target. The design and geometry may influence exposure. In terms of managing potential exposure in a nail salon context, a covered design is highly recommended for blocking the emission of blue light from a nail lamp. Eye protection (with blue blocking filters) may be useful for nail technicians.

4.6 CONCLUSIONS AND RECOMMENDATIONS

Blue light exposure in nail salons were found to be within existing guidelines, however, the nail technicians with long term blue light exposure from nail lamps may be at higher risk of photoreceptor damage.

The results showed that the blue light hazard from LED nail curing lamps could differ depending on types of lamp, and position.

Owing to the potential variability of viewing times and radiances, and the uncertainties associated with long term effects, longitudinal epidemiological studies on populations exposed to significant blue light sources need to be conducted.

In terms of managing potential exposure in a nail salon context, a covered nail lamp is recommended for blocking the emission of blue light from the nail lamp.

Chapter 5: Case Study 2 (Video production studio)

This case study refers to a complex multi-light source environment, where the end user may have greater or lesser exposures depending on the type of video production undertaken. Assessment of exposures to blue light sources was conducted using three exposure scenarios. Key considerations were the determination of the OVF and exposure time activity patterns with eye/head movements for a presenter(s), who are exposed to fixed-position light sources in the video production studio.

5.1 OBJECTIVES OF CASE STUDY 2

The objectives were to:

(1) Characterise the emission of bright light sources used in the video recording studio,

(2) examine three common exposure scenarios based on the observational data, and

(3) evaluate potential blue light exposures of users of the studio.

5.2 INTRODUCTORY BACKGROUND RELATED TO WORKERS IN VIDEO PRODUCTION

With the development of the computer-aided learning, new demands for training or teaching materials are growing at least as rapidly in education as it is in other fields. Online courses using video content are one of those developments and the video recording studio is used by many universities for their online classes. This teaching method enables students to actively participate in classes from anywhere.

In video recording studios, bright artificial light sources are generally used to get a clear and clean image, with proper colour rendition. Sources such as white LEDs or beamlights emit blue wavelengths that can cause retinal photochemical damage (Bonner et al., 2012, Hietanen & Hoikkala, 1990). Initially using oxy hydrogen light, also known as lime-light (also known as Drummond light), in 1839, there has been fast development of stage-related light sources in accordance with their intended use (Bond, 2008). From floodlights for large-scale night sport games or auditoriums to small studio light fixtures for “me-media” (one person’s content) such as YouTube videos, blogs or photographs, there are various types of light sources for stages or studios with many different sizes and functions.

According to reports of Job Outlook in 2017, over 50,000 Australians work in video studios and broadcast-related industries such as news anchors, entertainers (actors, singers and dancers), performing arts technicians, film, television, stage-related workers and lighting technicians in broadcasting stations (Job Outlook, 2017). Depending on tasks or working durations, these workers can be exposed to the bright studio light sources during recording and may be more at risk of retinal damage than other workers. Unfortunately, there appears to be no published report of a study related to blue light hazards from light sources in video production studios in Australia.

Bonner et al. (2011) reported that although the range of regulations regarding light sources in the entertainment industry is very comprehensive it is a complex task to determine workers’ exposure to optical radiation in entertainment venues. They reported that the levels of blue light varied depending on the direction of a person’s gaze, distances and locations of lightings in the stages (Bonner et al., 2011).

O’Hagan and Khazova (2011) undertook experiments to evaluate the levels of blue light in a Newsroom, a similar lighting environment to a video studio. The levels of the blue light for news presenters, journalists and supporting staff, did not exceed the exposure limit (100 W/m^2sr, $t > 10{,}000$ sec) and there was no foreseeable risk of overexposure. However, it was commented that there were significant different contrasts of the level of the illuminance and there were potential safety issues in some specific areas between dark and bright areas (O'Hagan & Khazova, 2011). The exposures of both the above studies were measured using ICNIRP guidelines for an 8-hour working duration.

In general, video recording studios in universities are much smaller in dimension than commercial stages, and the distances between performers/presenters and the light sources tend to be closer. In particular, the occupational visual fields in the video studios are likely to be quite different than for the larger stages.

Through two research approaches, in this study, potential blue light exposures of a presenter(s) were assessed within the OVFs and time activity patterns.

5.3 EXPERIMENTAL METHODS

Field Observation in a video production studio

For the case study, preliminary research was conducted to understand types of light sources and the general process for recording video materials and to collect exposure information related to studio lighting.

The video recording studio in the University of Adelaide was visited in June 2017 to observe lighting environments such as types/directions of light sources and to measure the sources and identify recording processes in the studio. Unlike the previous observations conducted in nail salons in Chapter 4, in this case study, the observations and the measurements needed to be conducted simultaneously due to the limited studio availability. In this situation, all light sources were installed in the ceiling and the light emitting from the light sources were not towards the eyes of a presenter if the presenter did not look at the light sources directly (Figure 5.1).

Figure 5.1 An example of the video recording studio at the University of Adelaide

The video recording studio was divided by two stages: a front stage for static presentations and a stage toward the back for dynamic presentations, respectively, and the dimensions of the studio were 6 m (L) ×5.6 m (W) ×2.9 m (H). With this design of the studio, the light sources were set up at two directions along the front and the rear stage. Figure 5.2 is the studio layout showing the locations of all light sources used in the studio and the numbers marked in red denote the light sources that were measured to identify the potential blue light exposure in the front stage. In this study, only nine light sources used in the front stage (no. ① - ⑨ in Figure 5.2) were considered because the study was focused on the potential blue light exposure of the presenters doing a video recording for the static presentations in the fixed position (e.g. academic lecture or sit-down interview) (Figure 5.2).

The information related to the studio, such as light sources and recording processes, were obtained from the officer in charge of the studio. Exposure case scenarios were created from observational data, e.g. numbers and locations of presenters, recording duration or types or light sources while recording. Three common scenarios were selected.

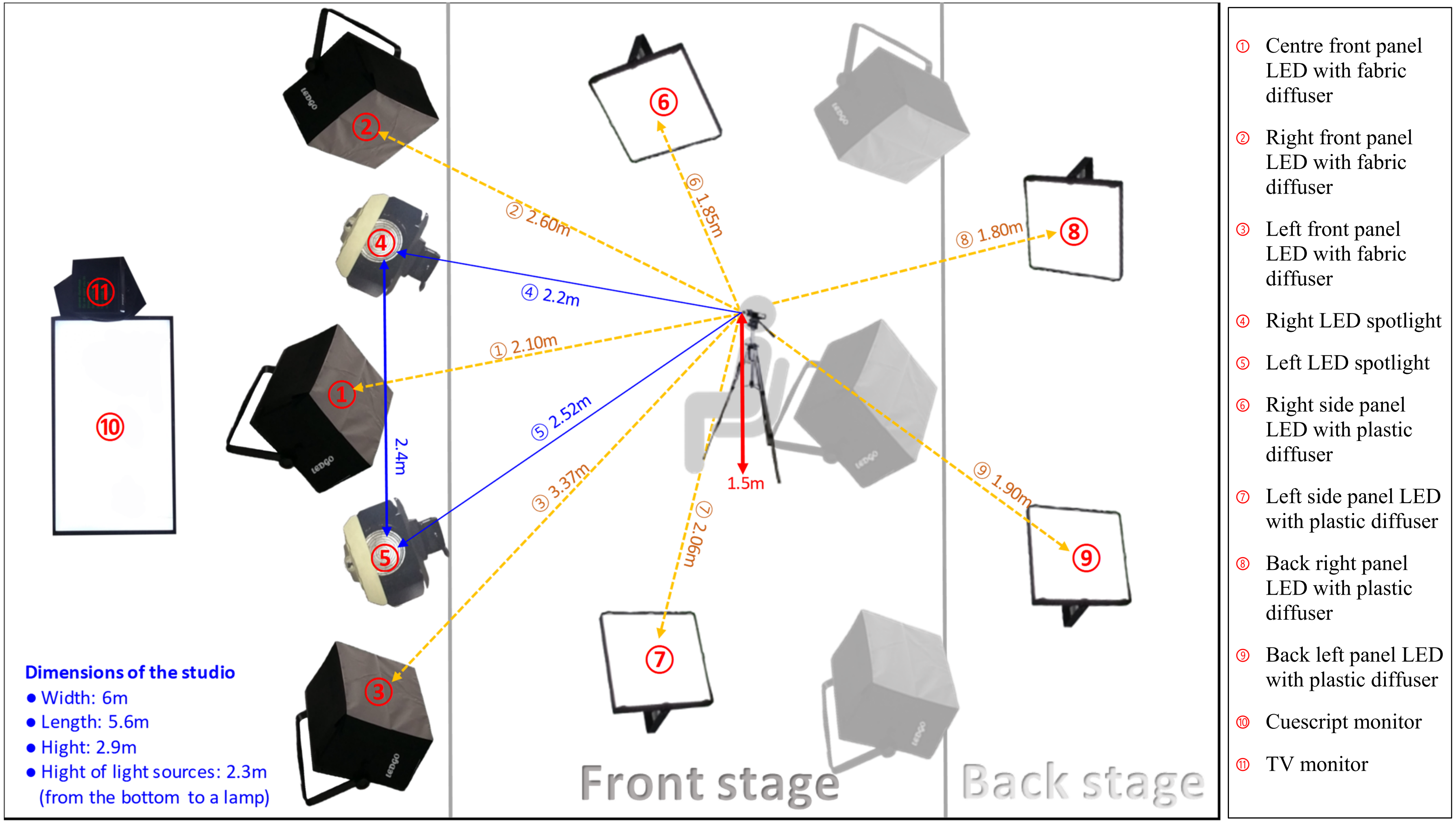

Figure 5.2 Floorplan and light sources in the video recording studio

Instrumentation for light measurement

A spectroradiometer, Specbos 1211 UV (JETI Germany, S/N: 2010143), was used to measure the spectral radiance (L_{BS}) of all light sources in the video recording studio. The spectroradiometer was set up at 150 cm from the floor in the centre of the stage.

National lux tester (National Company, BN-2000LTE, S/N: 000482) and Minolta luminance (Konica Minolta company, S/N: 401626) meter were also used to measure the levels of illuminance and luminance in the studio and the levels were measured in the same location as the spectroradiometer.

Characteristics of typical light sources (panel type of LED) in the video recording studio

Ten panel LEDs (LEDGO 900 PRO Series LED 5600K Studio Video Panel with DMX, LG-900S) and two LED spotlights (LEDGO LED Fresnel Light 5600K with DMX, LG-100FA) were installed in the ceiling of the studio. The set-up of lighting in the studio was as follows; to dim the direct emission of the light sources, six front and middle panel LEDs were covered with a white fabric diffuser and four panel LEDs at the back of the studio were covered with white plastic filters. Two spotlights were located on both sides of the front studio. The sizes of panel LEDs and spotlights are 45 x 45.5 x 8.5 cm (width x length x height) and around 39 x 23 x 19 cm respectively.

All tests were conducted within the video recording studio (Table 5.1). Figure 5.3 shows photos of a LED panel and a LED spotlight in the studio and the range of the radiance of a LED spotlight. General illuminance levels measured in the studio are summarised in Table 5.2. Colour temperatures of LED panels and LED spotlights ranged from 5000 to 6100 K for daylight type LEDs (Pearce, Crichton, Mackiewicz, Finlayson, & Hurlbert, 2014). The levels of illuminance were from 250 to 1110 lux and depended on types of light sources, locations, distances (Table 5.2).

Table 5.1 Emission characteristics of LED panels and spotlights as reported by the manufacturer and measured in this study using a luminance, lux meter and spectroradiometer.

	Measurement	LED panels	Spotlights (LED Fresnel Light)
LEDGO company (reported values)	Illumination (LM)	3850	7010
	CCT (K)	3200/5600	5600
Luminance meter with filter (Minolta)	Blue-weighted luminance (cd/m^2)	80-163	2569
Spectroradiometer Specbos 1211UV	Luminance (cd/m^2)	2400 – 13550	227500
	CCT (K)	5100 – 6100	5586
	Blue-weighted radiance L_B (W/m^{2}sr)	1 - 11	173

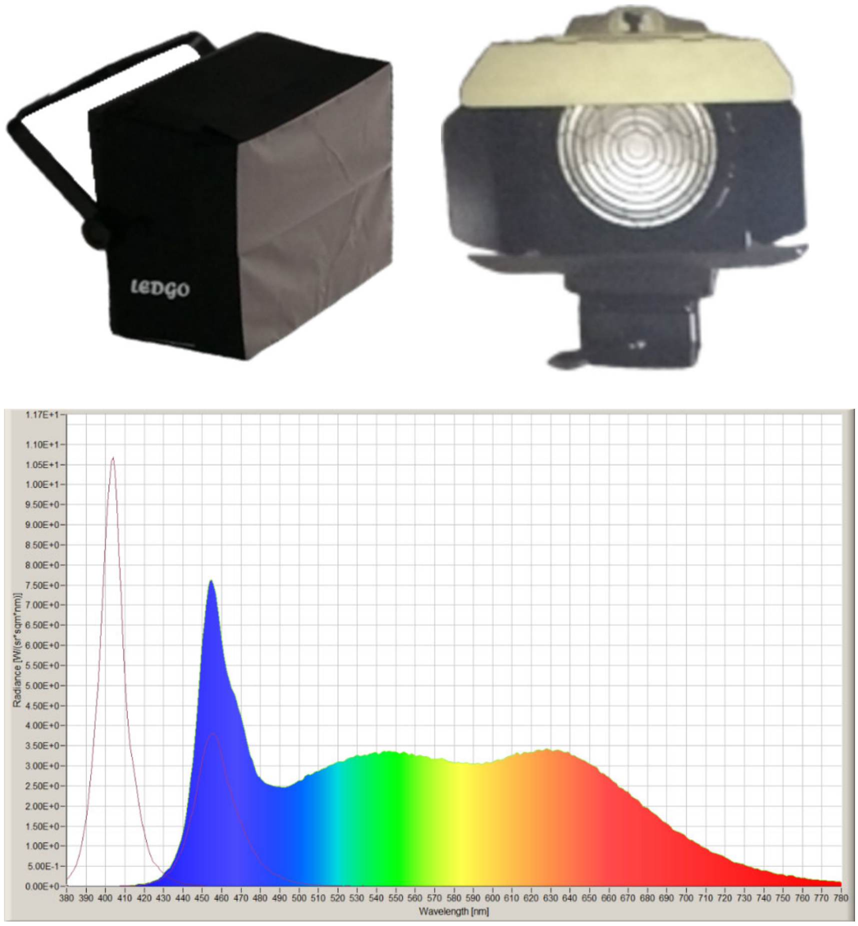

Figure 5.3 A LEDGO LED panel (top left) and LED spotlight (top right) and an example of the power spectrum of the LED spotlight (bottom)

Table 5.2 General levels of Illuminance in the studio

Index	Type of light	Location	Illuminance (lx)
Lx1	Ledgo 9 LED panels	On the chair: central position	513
Lx2	Ledgo 9 LED panels	At table height: central position	457
Lx3	Ledgo 9 LED panels	Eye level: 1.5 m, central position	450
Lx4	Ledgo 2 spotlights	Eye level (Presenter): central position	256
Lx5	Ledgo 2 spotlights	Eye level (Presenter): central position toward screen	1110
Lx6	Ledgo 2 spotlights	Eye level (Presenter):central position forward facing spotlights	911
Lx7	Ledgo 2 spotlights	On the chair: central position	110-113

Characterising the occupational visual field (OVF) and time activity patterns

A presenter (or presenters) using the studio have various working distances, angles and duration under studio lights. Depending on working distances between the eyes and light sources, various viewing angles of the presenter should be considered in their OVFs while recording video material in the studio. Unlike the OVFs of nail technicians who work at short working distances (30 – 40 cm), the presenters in video production have longer working distances (within 2 – 3 m) from their position to the lights. The patterns of the eyes and head movements of the presenter in the recording studio are also different from the OVFs of nail technicians who work closer to the light source, within 20 - 30 cm.

For these reasons, a larger and more spatial OVF than in the earlier chapter should be considered for the presenter in a video recording studio context. Based on the ‘occupational fixation zones’ (OFZ) described by Piccoli el al. (2004), the viewing angle as the OVF was determined using the areas of the human central vision (within 40 degrees) and applied to the exposure scenarios (Figure 5.4).

In order to specify time activity patterns, the fixed recording duration was set a time limit of 1 hour (3600 sec) in the case scenarios. This was the standard value for end users of the studio (see below).

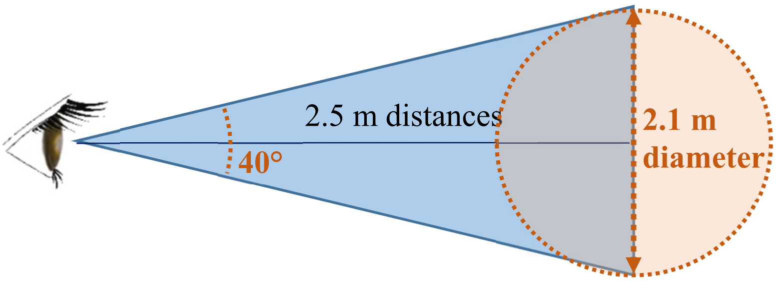

Figure 5.4 The Occupational Visual Field in the studio
(40 degrees marked orange dot-circle, Macular area in charge of the central vision (high-acuity and colour vision) at 2.5 m distance from the centre of the stage to the front viewing screen)

5.4 RESULTS

5.4.1 Case study set up

A total of twelve studio LEDs (ten panel LEDs and two LED spotlights) was set up on the ceiling of the studio for the video recording and four fluorescent ceiling lights were used for general background lights. Two LED spotlights and three panel LEDs covered by fabric diffusers were installed in the front ceiling for the front stage and three panel LEDs covered by fabric diffusers and two side panel LEDs were installed in the middle of the ceiling for the stage towards the back. The other two panel LEDs were placed at the end of the stage in the direction of the front wall (See Figure 5.2).

Based on the presenter standing in the centre of the front stage, the front light sources were located at 2.1 to 3.3 m distance. The size of the panel LED was around 30 cm square and a round-shaped spotlight source was around 15 cm in diameter.

Seven panel LEDs (three front, two middle and two rear LEDs) were generally used for the static presentation and two spotlights were used without other light sources for interviews or specific performances, such as a monologue.

The numbers of the light sources used in the section 5.4.3 Exposure assessment simulation are the same as the numbers of Figure 5.2 and the spectral radiances (L_{BS}) from these light sources were used for the calculations of the spectral radiance doses (D_{BS}) based on the time activity patterns in the exposure scenarios.

5.4.2 Characterising simple exposure scenarios

In order to assess the actual blue light exposure of a presenter in the studio, simplified exposure scenarios were created based on the working environments and patterns. Depending on the number of the presenters, the amount of exposure to the light sources and the range of visual fields can differ. Thus, simple but frequently-used types of video recording were considered.

The following factors are the key considerations which can affect lighting exposure while recording a video.

- Types of light sources

- Time activity patterns: durations and frequencies of the eye/head movements
- OVFs: the presenter's visual fields in accordance with working distances and viewing angles (40 degrees, the central visual field of the binocular vision, was applied in this study) (Piccoli et al, 2004)
- Number of presenters

Based on these considerations and the information from the observations, three simplified exposure scenarios were created, as follows:

- **Scenario 1. One presenter is under seven general panel LEDs**
- **Scenario 2. One presenter is under two LED spotlights**
- **Scenario 3. Two presenters were under seven general panel LEDs**

The recording durations can vary according to the booking time, but in this case 1-hour recording was considered in the exposure scenarios (e.g. length of a standard lecture). The estimated exposure durations for each scenario were also determined in the light of time-activity patterns.

There were four possible directions of the eyes/head movements of one single presenter during 1-hour recording: (1) looking at a script monitor, (2) watching the recording on a TV monitor, (3) often checking the recording time, and (4) looking at the studio front door. In scenario 3, two different directions of the exposure situations for the two presenters having a discussion were estimated.

Table 5.3 details all exposure scenarios including estimated exposure duration and the potential blue light exposure, as evaluated by these simplified exposure scenarios using the experimental data of the light sources in the studio.

Table 5.3 Exposure scenarios while recording for 1-hour

Scenarios in the video recording studio		Total recording duration (sec)	Estimated exposure duration (sec) /viewing	Exposure situations
Scenario 1	VS1_1	3600	2040	When a presenter gazes at a script monitor
	VS1_2		1500	When the presenter gazes at a TV monitor
	VS1_3		30	When the presenter gazes at a clock
	VS1_4		30	When the presenter gazes at the studio entry door
Scenario 2	VS2_1	3600	2040	When the presenter gazes at a script monitor
	VS2_2		1500	When the presenter gazes at a TV monitor
	VS2_3		30	When the presenter gazes at a clock
	VS2_4		30	When the presenter gazes at the studio entry door
Scenario 3	VS3_1	3600	1800	When two people are looking at a script monitor or TV monitor
	VS3_2		1800	When two people are talking to each other face to face

5.4.3 Exposure assessment simulation

The measurements of light sources (luminance, radiance and correlated colour temperature (CCT)) were conducted in the studio at the same time as the observational studies. In order to identify the potential amount of blue light exposure of the presenter(s) in the video studio, all light sources used for recording in a front stage were measured by the spectroradiometer and the detailed outcomes related to light emission from the light sources are set out in Table 5.4. Using the values of spectral blue-weighted radiance (L_B), the potential blue-weighted doses (D_{BS}) of the presenter(s) were calculated in each exposure scenario in terms of time-activity patterns within 1-hour.

As mentioned earlier in this chapter, the locations of the light sources with circled numbers are the same as the numbers in Figure 5.2.

Table 5.4 Characteristics of photometric & radiometric quantities of the studio lighting

Index (Light source No.)*	Types of light sources	Location of light sources	Distance from eyes (at 1.5 m height) (m)	Specbos on a tripod at height 1.5 m (fixed on a tripod)			
				Spectral blue-weighted radiance (W/m^2sr)	Luminance (cd/m^2)	Radiance (W/m^2sr)	CCT (k)
①	Ledgo panel LED with Softbox	Centre front	2.10	6.04	7775	28.50	5400
②	Ledgo panel LED with Softbox	Right front	2.60	7.00	9058	32.90	5511
③	Ledgo panel LED with Softbox	Left front	3.37	6.95	8831	32.06	5537
④	Ledgo LED spotlight	Right front	2.10	Over-exposure	Over-exposure	Over-Exposure	Over-exposure
⑤	Ledgo LED spotlight	Left front	2.52	173.20	227500	855.90	5586
⑥	Ledgo panel LED with white filter	Right side	1.85	10.80	12690	46.64	6112
⑦	Ledgo panel LED with white filter	Left side	2.06	11.29	13550	49.66	5924
⑧	Ledgo panel LED with white filter	Back right	1.80	2.30	2961	10.99	5323
⑨	Ledgo panel LED with white filter	Back left	1.90	1.81	2410	8.86	5280
⑩	Script monitor	Centre front	2.90	0.00	7	0.02	6168
⑪	TV monitor	Centre front	2.90	0.42	345	1.20	11816

Scenario 1. One presenter is under seven general LED panels

The first exposure scenario simulates a case in which one presenter records a video for 1-hour. This case is the common recording type used by academic lecturers for an online course and the results can be used in similar situations for one person's video.

In this scenario 1, it was estimated that the presenter stands up in the middle of the stage and looks straight ahead without body movements. In this situation, the levels of exposure to the light sources are dependent on the movements of the eyes and head of the presenter. The presenter looks at the script monitor most of the time, often checking the video recording by watching the TV monitor and keeping an eye on the time and the front door (there is a control office of the video studio behind the front door).

Based on the 2.9 m distances from a presenter to a front script monitor (teleprompter), a 2.1 m diameter of the OVF (40°, centre vision) was determined. The coloured circles in Figure 5.5 indicate the estimated ranges of the OVFs in accordance to the eyes/head movements of the presenter and light sources involved in each OVF. The yellow lined circle (S1_1) indicates the OVF when the presenter gazes at a script monitor, the violet narrow-dotted circle (S1_2) indicates the OVF when the presenter gazes at a TV monitor, the red wide-dotted circle (S1_3) indicates the OVF when the presenter looks at a clock and the last blue double dotted circle (S1_4) indicates the OVF when the presenter looks at the front door. In exposure scenario 1, there were three types of light sources which enter the eyes of the presenter; ① the centred front panel LED, ⑩ script monitor and ⑪ TV monitor. The levels of the L_{BS} of the light sources measured in the observational studies were ① 6.04 W/m^{2}sr, ⑩ 0.005 W/m^{2}sr and ⑪ 0.427 W/m^{2}sr, respectively. Using the exposure time activity patterns and the levels of the L_{BS}, the potential D_{BS} were determined in Table 5.5.

For the scenario, the total potential D_B of the presenter for 1-hour recording was 23,121 J/m^{2}sr and the most intense light sources which can affect photochemical damage was the panel LED in the front ceiling.

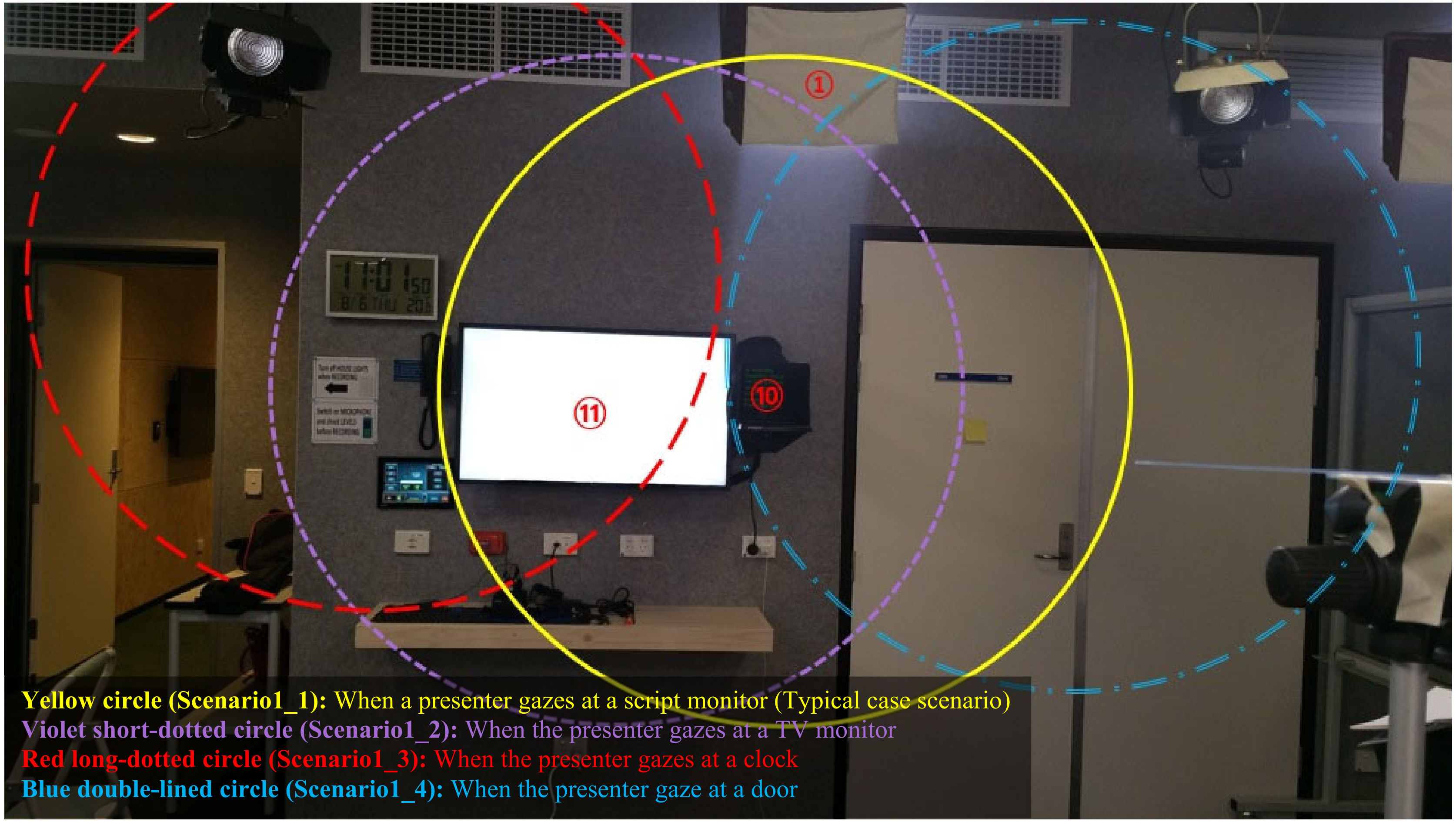

Figure 5.5 Estimated OVFs in exposure scenario 1

Table 5.5 Estimated spectral radiance dose (D_{BS}) of exposure scenario 2 for 1-hour recording

Scenario 1	Details	Light sources within the OVF (No.)*	Exposure duration /1-hour recording (3,600 sec)	Spectral radiance_ blue-weighted radiance (W/m²sr)	D_{BS} (J/m²sr)	Total D_{BS} (J/m²sr)
S1_1	When a presenter gazes at script monitor	①	2040	6.040	12321.60	13,204
		⑩		0.005	10.38	
		⑪		0.427	872.98	
S1_2	When a person gazes at TV monitor	①	1500	6.040	9060.00	9,709
		⑩		0.005	7.63	
		⑪		0.427	641.89	
S1_3	When a person gazes at clock	⑪	30	0.427	12.83	12
S1_4	When a person gazes at door	①	30	6.040	181.20	194
		⑩		0.005	0.15	
		⑪		0.427	12.83	
Total estimated D_B for 1-hour recording						**23,121**

* Light source numbers-determined in Figure 5.2

Scenario 2. One presenter under two spotlights

For the second scenario, one presenter was considered recording a video under two spotlights installed on both sides of the front ceiling. This case is often used when a presenter(s) record(s) a video such as a self-interview or monologues.

Excepting for the different type of light sources used in scenario 1, the exposure in scenario 2 assumed that all estimated exposure durations would be the same as scenario 1. When a single presenter stands up in the middle of the stage, records a video looking at the front script monitor, a TV monitor, a clock and a front door, relevant light sources could enter the eyes were considered. Unlike scenario 1, two LED spotlights emitted high levels of the L_B and the L_B of the right side spotlight was excessive and could not be read by the spectroradiometer.

The ranges of the OVFs (2.1 m diameters at 2.9 m distances from a presenter to a front script monitor) were determined as for scenario 1 and the coloured circles in Figure 5.6 were determined as for scenario 1. Figure 5.7 shows the LED spotlights which the presenter actually sees. S2_1 (yellow lined circle) indicates the range of the OVF when the presenter gazes at a script monitor for 30 min, S2_2 (violet narrow-dotted circle) indicates the OVF when the presenter checks the TV monitor, S2_3 (red wide-dotted circle) indicates the OVF when the presenter glances at the clock and the last S2_4 indicates the OVF when the presenter checks the front door. Three types of light sources (④&⑤ both sides of spotlights, ⑩ script monitor and ⑪ TV monitor) could expose the eyes of the presenter in the OVFs and the levels of the L_Bs of the light sources were ④ over exposure, ⑤ 173.2 W/m^{2}sr, ⑩ 0.005 W/m^{2}sr and ⑪ 0.427 W/m^{2}sr respectively. The potential D_Bs were 883 J/m^{2}sr (S2_1), 649 J/m^{2}sr (S2_2), and 5,204 J/m^{2}sr (S2_3) respectively. The total potential value of the D_B of the exposure scenario 2_4 was calculated using the L_B of the number ⑤ left side spot light because ④ right side spotlight could not be measured by the spectroradiometer (it was over-exposure by Specbos). Thus, the total amount of blue weighted radiance dose (D_B) of the exposure scenario 2 is estimated to be over 11,940 J/m^{2}sr (Table 5.6).

The levels of L_B of LED spotlights exceeded the exposure limit, 100 W/m^{2}sr, within 8 hours working duration a day, however, the total D_B did not exceed the limit, 10^6 J/m^{2}sr. The spotlights emitted very intense blue wavelengths but the presenter generally looks at the front script or TV monitor during the recording of the video. In terms of the OVFs, the radiances of both spotlights could enter the eyes when the presenter only checks the time or the door and the viewing durations were estimated at around 60 sec (1 min) for a 1-hour recording.

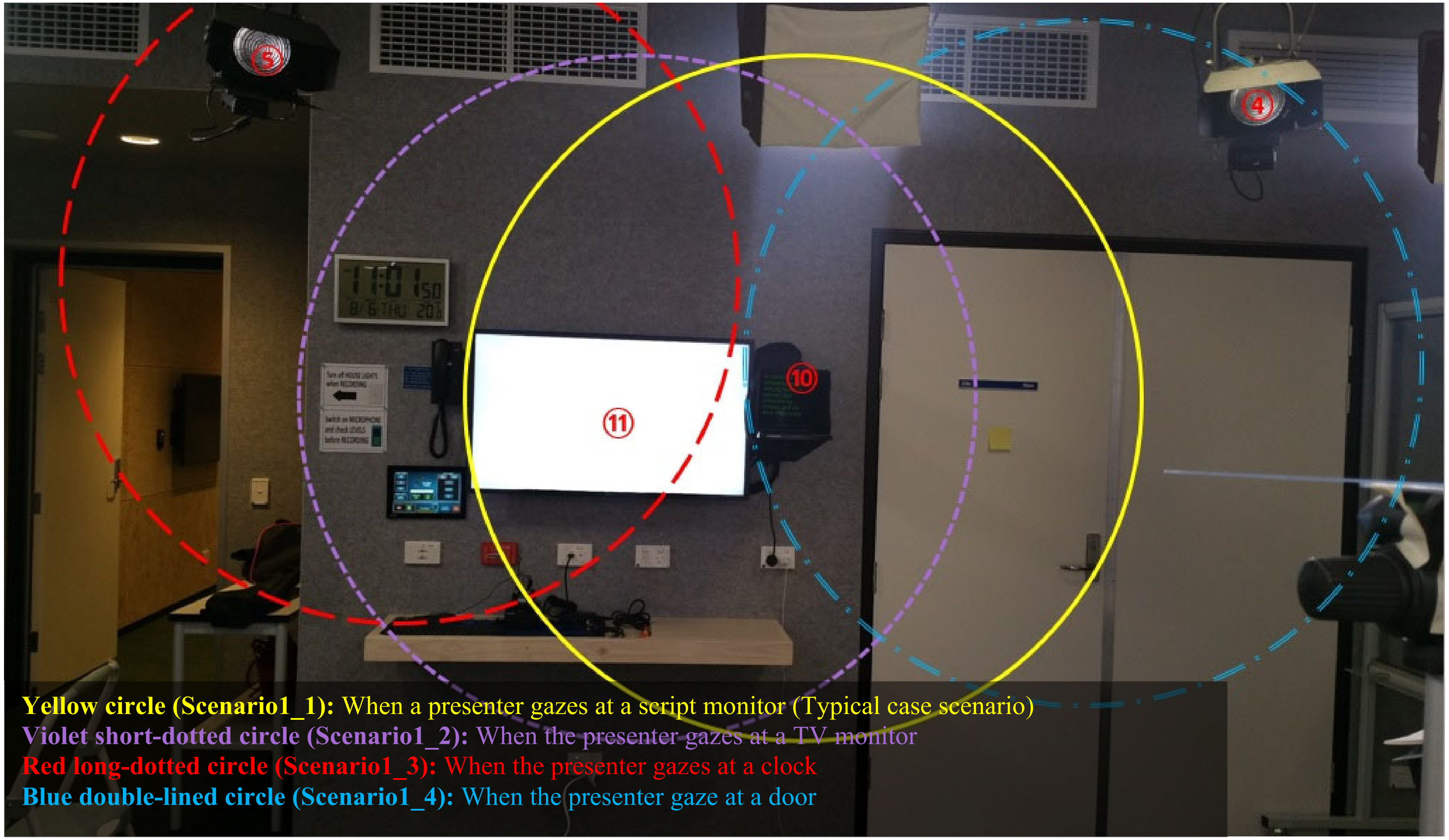

Figure 5.6 Estimated OVFs in exposure scenario 2

Figure 5.7 An example of actual viewing of spotlights for scenario 2.

Table 5.6 Estimated spectral radiance dose (DBS) of exposure scenario 2 for 1-hour recording

Scenario 2	Details	Light sources within the OVF (No.)*	Exposure duration /1-hour recording (3600 sec)	Spectral radiance_ blue-weighted radiance (W/m^2sr)	D_B (J/m^2sr)	Total D_B (J/m^2sr)
VS2_1	When a presenter gazes at the script monitor	⑩	2,040	0.005	10.38	883
		⑪		0.427	872.98	
VS2_2	When a person gazes at the TV monitor	⑩	1,500	0.005	7.63	649
		⑪		0.427	641.89	
VS2_3	When a person gazes at the clock	⑪	30	0.427	12.83	5,204
		⑤		**173.200**	5,190.00	
VS2_4	When a person gazes at the door	⑩	30	0.005	0.15	Over S2_3
		④		Over-exposure	Over-exposure	
Total estimated D_B for 1-hour recording						**Over 11,940**

* Light source numbers-determined in Figure 5.2

Scenario 3. Two presenters under seven panel LEDs

The third exposure scenario considered two presenters having a face to face discussion under seven panel LEDs. Two chairs 1 m distance apart were set up in the middle of the stage and the condition of the background light sources was the same as for exposure scenario 1 (Figure 5.8). Unlike the earlier two scenarios, the time activity pattern over 1-hour of recording was comprised of two viewing directions: 30 min for when the presenters talked facing each other, and 30 min for when the presenters gazed toward the front such as reading scripts on the front script monitor (see Table 5.3). In other words, two different OVFs per presenter were considered in this scenario. Figure 5.9 shows the range of the OVF of the left presenter. When the two presenters look at the front area (exposure scenario 3_1), e.g. a script monitor or TV monitor, the front ① panel LED is the strongest light source which can affect the retinal exposure of both presenters. When two presenters talk to each other (exposure scenario 3_2), the ③ panel LED can be in the OVF of the left presenter and the ② panel LED can be included in the OVF of the right presenter (see Figure 5.9).

In summary, there were four light sources which could enter the eyes of the presenters; ① the centred front panel LED, ② the right front panel LED, ③ the left front panel LED, ⑩ cue-script monitor and ⑪ TV monitor (Figure 5.10). The L_{BS} of these light sources measured in the observational studies were ① 6.04 W/m^{2}sr, ② 7 W/m^{2}sr, ③ 6.95 W/m^{2}sr, ⑩ 0.005 W/m^{2}sr and ⑪ 0.427 W/m^{2}sr respectively (see Table 5.3). Using the exposure time activity patterns within 1 hour recording duration and the levels of the L_{BS}, the potential D_{BS} were determined in Table 5.7.

In results of the scenario, total potential D_{BS} of the presenters for 1-hour recording were 24,161 J/m^{2}sr for the left presenter and 24,251 J/m^{2}sr for the right presenter, and the most intense light sources which could cause photochemical damage were the three panel LEDs installed in the front ceiling.

Figure 5.8 An example of scenario 3 (left: left presenter, right: right presenter)

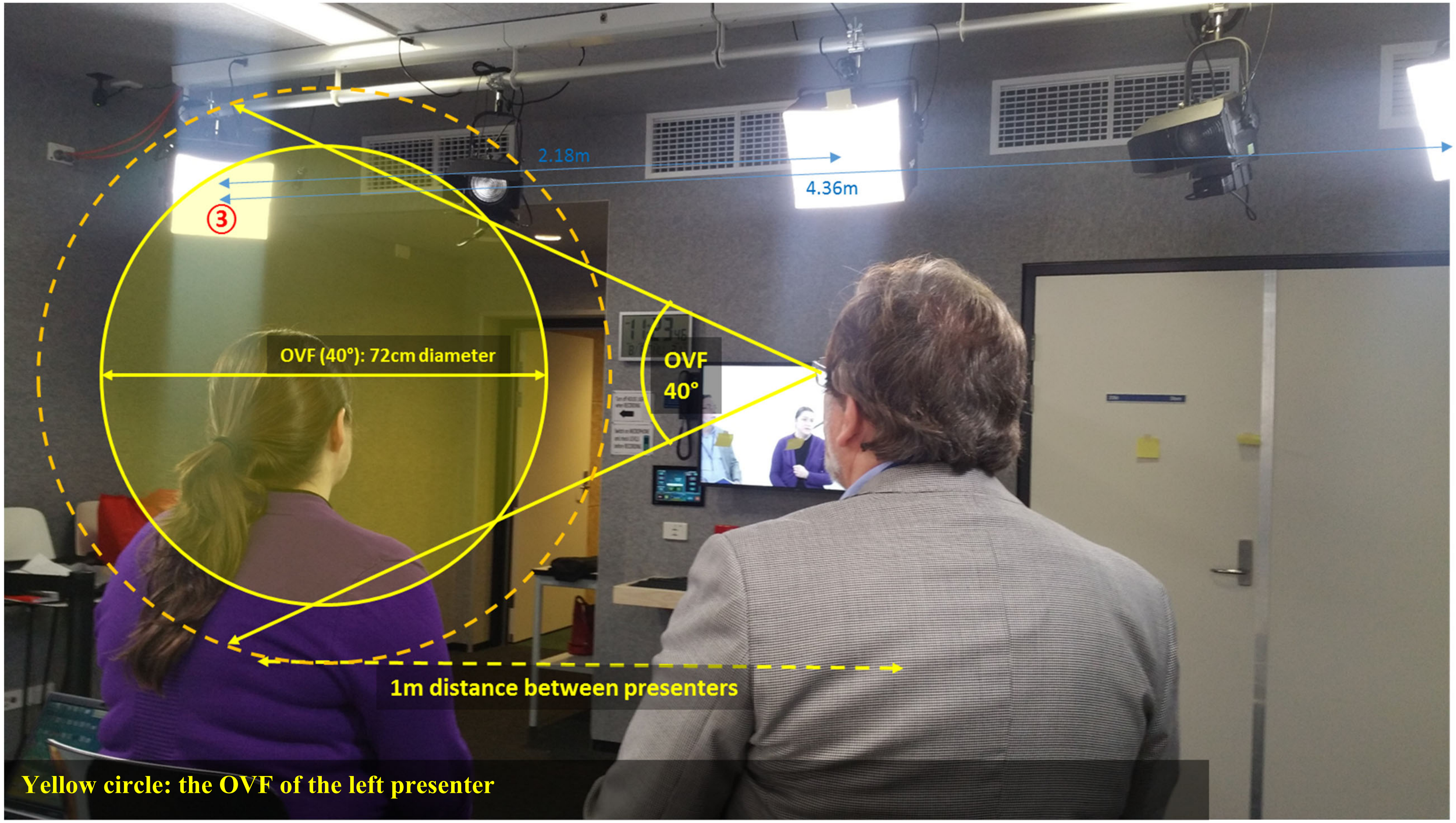

Figure 5.9 The potential OVF of the right presenter if they were gazing the left presenter

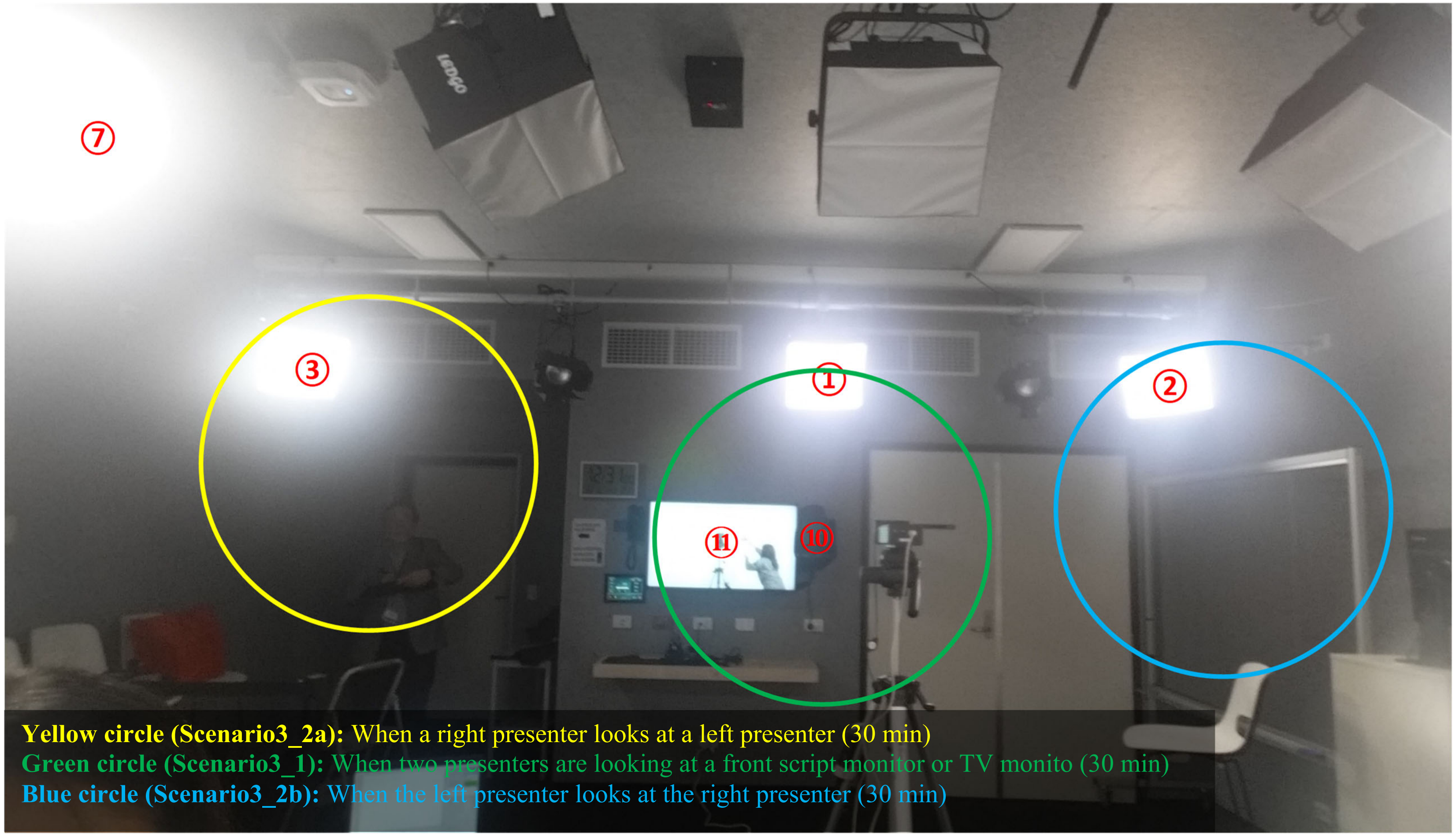

Figure 5.10 Light sources in the OVFs in accordance with viewing points of both presenters

Table 5.7 Estimated spectral radiance dose (D_{BS}) of exposure scenario 3 for 1-hour recording

Scenario 3		Details	Light sources within the OVF (No.)	Exposure duration /1-hour recording (sec)	L_B (W/m^2sr)	D_B (J/m^2sr)	Total D_B
S3_1	Left presenter	The left presenter/the right presenter is looking at a script monitor or TV monitor	①	1,800	6.040	10,872	11,651
			⑩		0.005	9	
			⑪		0.427	770	
	Right presenter		①		6.040	10,872	11,651
			⑩		0.005	9	
			⑪		0.427	770	
S3_2	Left presenter	Two presenters are talking to each other face to face	③	1,800	6.950	12,510	12,510
	Right presenter		②		7.000	12,600	12,600
Total estimated D_B for 1 hour recording for the left presenter							**24,161**
Total estimated D_B for 1 hour recording for the right presenter							**24,251**

* Light source numbers-determined in Figure 5.2

5.5 DISCUSSION

Video production studios are being used in many universities for the purpose of recording videos such as class projects, online courses, presentations, interviews or group discussions. The studio is basically designed to be used by many people, who may not be experts in, or even aware of, the lighting technology. There are various types of blue/white light sources in the studios and it is not straightforward to be able to appraise actual/potential photochemical risk to the eyes of the users or workers who use or work in the studios.

Three different exposure scenarios at the Adelaide University's studio were standardised for assessment. The aim of the lighting is to ensure video quality and no specific consideration is generally given to hazards associated with the lighting. Generally, studio usage time for users is around 1 to 2 hours per day. Following a discussion with the manager of the facility, it was evident that the purchasing of the lamps and the setting up of the system entailed an assumption that light sources do not represent a hazard to the eyes. However, there is the potential for excessive exposure, depending on the lamps used, their light spectrum, their intensity and whether they are in the visual field of the user. Therefore, the purpose of this case study was to ascertain studio users' exposures according to scenarios, using a rigorous approach, described in this Chapter.

As all light sources were installed in the ceiling, the light emitting from these sources were at a significant angle to the eyes of a presenter and were not viewed directly unless the presenter inadvertently looked directly at them. The absolute levels of exposure on the retina to blue light from the light sources in the studio can vary according to the angle of sight/viewing as discussed in Chapter 2, and the size of the OVF can also vary depending on distances between the eyes and light sources.

In reality the presenter(s) using the video studio had larger viewing angles and a larger range of eye movements than nail technicians in the previous chapter. For these reasons, the human central vision in the binocular field (40 degrees, macular area in the retina) (Piccoli et al., 2004) was considered as the OVF of the presenter(s). The assessments of the exposure to blue light sources of three simplified exposure scenario were considered in the OVF.

It was found that in all scenarios, the integrated blue light exposures were less than the current ICNIRP guidelines. In total for nine light sources (numbered from ① to ⑨ in Figure 5.1), the most frequently involved blue light source in the OVF was a ① LED panel, front and centre-located, when the presenter(s) stared towards the front in the exposure scenario 1 and 3. However, the L_B of the ① LED panel did not exceed the limit, but the spotlights had radiances greater than the radiance limit of 100 W/m^{2}sr.

It appears that there are **only two peer-reviewed papers** referring to blue light hazards in studios with multiple light sources.

Hietanen and Hoikkala (1990) reported effective blue-weighted spectral radiances (L_Bs) of photoflood metal halides and halogens lamps used in TV studios and theatres and their permissible daily exposure times (t_{max}s). All of these lamps gave measured radiances, exceeded the limit of L_B, and the range of the permissible exposure durations of the photofloods was from less than 1 minute up to 3 hours. Based on the measurement results, they recommended that workers who are working in TV studios and theatres including maintenance personnel, would need eye protection if exposed to the lamps while working. They also recommended the use of special contact lenses that screen out the blue wavelengths for the workers, such as for announcers or theatre actors/actresses, who are required to look towards the front where lighting is most concentrated (Hietanen & Hoikkala, 1990).

Unfortunately, due to the large number of variables in studio lighting environments, existing regulations (European Union, 2006), guidelines (ICNIRP, 2013) or TLVs (ACGIH, 2015) for assessing the exposure to blue light, it is difficult to assess the actual amount of an individual exposure to blue light in entertainment-related workplaces. Bonner et al. (2012) assessed personal exposures to non-laser optical radiation on large-scale stages. For practical risk assessment, they created exposure scenarios considering distance, position and likely duration. Their risk assessment used a simplification of measurements, e.g. closest distances, staring directly at light sources, 8-hour working duration, unrestricted visual field and acceptance averaging angle (0.01 radians) for assessing blue light hazard for the personal exposure scenario (Figure 5.11).

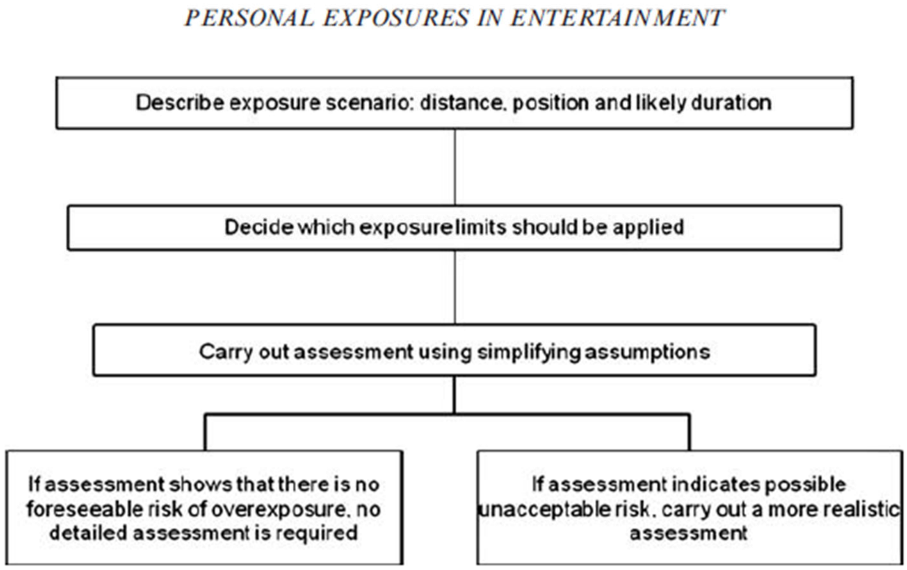

Figure 5.11 Generic approach for practical risk assessments (Bonner et al. 2012, page 227)

Using spectral irradiances (E_λs) of stage lamps, UV and blue light hazard were analysed in each spectral range, e.g. 250 - 400 nm for UVA and 300 - 700 nm for blue light. In order to understand the applicable optical radiation hazards, hazard ratios were calculated using the E_λs and illuminance levels. In Bonner's study, blue LEDs and white LEDs on a stage substantially exceeded the limit of E_λ, 1 W/m^2 within 8 hr, and the maximum permissible exposure (MPE) times were only 2.5 min for the blue LED and 13 min for the white LED luminaires (the worst case) within an 8-hour day. However, the exposure to blue light for a performer depended on the distances and viewing targets (e.g. looking up/down/right/left). They concluded that the risk of blue light exposure for the performers and crew is very low but the direct viewing of intense sources would likely be highly hazardous for the eyes. It was also mentioned that the high contrast between illuminance conditions should be considered due to safety concerns (e.g. to prevent slips, falls and bumps), and recommended that more detailed risk assessment is required to mitigate the potential risks of individual workers (Bonner et al., 2012).

Although both of the above studies showed the potential exposure to blue light in the actual TV studios or large entertainment venues, they did not take into account the visual fields and exposure time activity patterns for the performer(s) on the stage. The radiance and irradiance of the light sources were only targeted directly (as the worst case). Indeed, it is very difficult to keep track of actual exposure levels of the amount and intensity or frequency of the blue light for individual persons working in TV studios or large entertainment venues. Thus, this study focused on developing more practical exposure assessments of blue light sources in the video recording studio. The major differences from the existing literature were the determination of the OVF and actual exposure time activity patterns for the presenter(s) using the studio. Based on three exposure scenarios, more likely D_Bs were calculated using simplified viewing targets of the presenter(s) during a 1-hour recording, and various factors, e.g. various viewing durations, individual eye/head movements, gestures of the presenter, etc., were considered to assess actual exposure levels.

The spectroradiometer (Specbos with OD 2.5 filter) is limited in measuring highly intense light sources and the L_Bs of the LED spotlights indicated over-exposure. The highest measurable L_B of the LED spotlights was 173 W/m^{2}sr. Thus, the actual L_B can be higher than 173 W/m^{2}sr - this value exceeds the limit of the acceptable exposure (100 W/m^{2}sr) during an 8-hour working duration. This study only focused on the potential retinal photochemical risk from exposure to blue light sources in the video recording studio. Other health effects related to circadian rhythm, skin effects or retinal thermal damage from the blue light and the possible synergistic effect caused individually by many “photosensitizing drugs” such as amiodarone, psoralen, tetracycline, phenothiazine, etc., were not considered.

5.6 CONCLUSIONS AND RECOMMENDATIONS

Using the three simple exposure scenarios, a risk assessment for potential retinal damage in the video production studio was conducted. The initially measured L_Bs of the all light sources in the studio were used to assess the D_Bs of the three exposure scenarios. All D_Bs of the exposure scenarios were within permissible levels (10^6 J/m^{2}sr) of blue light hazard provided by ICNIRP guidelines within the acceptable exposure duration per day, but the LED spotlights exceeded the radiance limit of 100 W/m^2sr. Based on the results, the LEDs in the studio are not likely to cause risks to the retina directly. However, it is hard to define that there is no retinal risk from the exposure to light sources in the studio because of various light exposure environments (e.g. light sources in the OVF) and different types of recording situations (e.g. gaze directions of presenters, recording styles or numbers of presenters).

These findings of this study relate to workers such as actors/actresses performing in little theatres, news anchors in a news studio, users using small studios who are exposed to studio lighting.

Several suggestions for the studio lighting situation can be made:

- For new designers: companies could manufacture safer light sources to eliminate the range of blue wavelengths, especially in the 441 nm region that can damage the retina; set the locations of intense blue light sources (e.g. LED spotlights in this case study), considering the OVF, to minimise possible direct exposure of the presenter(s) eyes.
- For users: Universities should provide appropriate information/training on the potential photochemical risks from exposure to the blue light sources for all users of the studio. Relevant training may be necessary to understand and thus reduce the risk of retinal damage from exposure to the blue light sources. Appropriate eye protection (e.g. blue light protective glasses or perhaps contact lenses) could be worn to protect against the potential risk of the retinal injury for heavy users.

More detailed information considering presenters' individual OVFs, time activity patterns, types of studio lighting depending on the purposes of recordings are recommended in future studies.

Chapter 6: Case study 3 (Dental simulation clinic)

Dental curing lamps are intense blue light sources, used for the curing of composite resins. Dental students repeatedly use these handheld lamps as part of learning (e.g. simulation clinics) potentially with limited supervision and awareness of the blue light hazard. This chapter address blue light exposure in a simulation clinic.

Preliminary observations were made in a university dental simulation clinic to understand student procedures in more detail, including the use of lamps and shielding, and to determine time-activity patterns and exposure geometries. Worst case and typical scenarios were simulated in the laboratory and blue light effective radiances (L_B) were measured using a spectroradiometer. Two commercially available blue-light protective glasses were also tested for blue light attenuation. Values often exceeded the radiance limit of 100 W/m^2sr. It is recommended that blue-light protective glasses be worn and that training include more information on the nature of the blue light hazard and control measures.

6.1 PURPOSE OF CASE STUDY 3

The objectives of this study were to:

[1] characterise the potential blue light exposure to dental curing lamps in a dental simulation clinic at the University of Adelaide, taking into consideration time activity patterns and geometries of work activity

[2] compare exposures with ICNIRP/ACGIH TLV guidelines.

6.2 INTRODUCTORY BACKGROUND

Dental curing lamps are intense blue light sources, used for the curing of composite resins and there are three types of dental curing lamps: halogen, plasma and LEDs. Since 1980, the potential ocular hazard from the dental curing lamps has been considered from the use of the initial quartz-tungsten-halogen (QTH) curing lamp. From that point on, plasma and LED sources became more affordable and more studies related to their hazards have been conducted (Labrie et al. 2011; McCusker et al. 2013; Price et al. 2016). Currently, the use of LEDs is the most common of the three main types of dental curing lamps.

In 2017, there are 22,383 registered dental practitioners in Australia and 89.5 % of the total practitioners are in the 25-59 age range. (Australian Health Practitioner Regulation Agency 2017). Thousands of students and staff are also studying and teaching in dental-related schools. Dental students, in particular, use these handheld lamps repeatedly as part of simulation clinics, and they must be able to cure resins at various angles in the mouth. Students thus may be more at risk of eye injury from the use of these lamps than professional dental practitioners because of a lack of safety knowledge/technique due to limited field experience. One US survey study in 2006 showed that only 84 percent of respondent dental schools provided blue light protective glasses to protect students' eyes from exposure to curing lamps during lab procedures. The survey emphasised that all dental schools should provide continuous safety education to students for protection of their eyes (Hill, 2006). Unfortunately, however, there are currently no studies (either practitioners or students) about the potential ocular hazards/risks from UV/blue light exposure to dental curing lamps in Australia.

Two Australian standards, AS/NZS 1337 and AS/NZS 62471, provide the technical information of personal eye protection and lighting designs in workplaces respectively showing some practical information for eye protection from various exposures to different wavelengths of light, e.g. UV or IR. (AS/NZS IEC 62471, 2011; AS/NZS 1337.1, 2014) However, the standards related to the protection method for the hazardous light exposure are not part of regulatory requirements.

Potential retinal photochemical damage from the dental curing lamp has been described in many experimental studies. The studies measured various types of dental curing lamps, as previously mentioned, at various distances from 10 cm to 1 m

(Bruzell Roll, Jacobsen & Hensten-Pettersen 2004; Labrie et al. 2011; Price et al. 2016) and at two different angles (e.g. direct and indirect path of the light from the curing units to the operators' eyes) (Labrie et al. 2011). The maximum permissible exposure times to blue light varied from 6 sec to 100 min depending on angles, distances (Labrie et al. 2011; McCusker et al. 2013). Most papers recommended appropriate protective eyeglasses from exposure to dental curing lamps emitting intense blue wavelengths. Moseley et al. in particular, estimated that the light of a dental curing lamp was reflected by 30 percent at 30 cm distances from the treated tooth to the operator's eyes and estimated maximum permissible exposure durations per day were between 40 and 100 min (Moseley, Strang & MacDonald 1987). The levels of the exposure can differ depending on the angle of light direction, the distance to the light sources, the types of dental curing lamps used, as well as the anthropometric characteristics of the operator (Bruzell Roll, Jacobsen & Hensten-Pettersen 2004). The levels of the potential effective spectral radiances (L_{BS}) of a dental curing lamp can depend on various exposure factors, e.g. angles, directions or durations of usage of a dental curing lamp. Generally, the working distance of dental students is very close and thus, the visual field for the students is narrower than the 'normal' visual field and the retinal damage risk can be higher. Potential blue light hazards should be determined in the occupational visual field (OVF) (Piccoli et al. 2004) and previous research has not explicitly considered this.

6.3 EXPERIMENTAL METHODS

The same approaches with the two previous case studies using preliminary research, observational studies and simulations were conducted in this case study.

Preliminary research for understanding dental simulation process

Before the field observations began, initial information regarding a dental curing lamp and its use were investigated by formal literature review and Internet search. Typical and worst case scenarios, in terms of direct and indirect viewing of the curing light between the tooth-treated and the point of operator's nasion, were considered for the observational studies. Specific information about the training courses in the dental school were collected from the supervising administrative officer in the dental simulation clinic and the health and safety manager at the University of Adelaide.

Field Observation and curing processes in the Dental Simulation Clinic

The dental simulation clinic of the University of Adelaide was visited five times from 24 Oct 2017 to 19 Apr 2018 to conduct observations in the clinic and to do simulations using a dental curing lamp on the standard mannequin mouth. The observations were conducted without any interruptions to students' procedures and there were no ethical issues during the observations. Worst case and typical scenarios were created from observational data, e.g. time activity patterns and frequency of use of a dental curing lamp during the training courses. The on-site inspections revealed that no other blue-light sources where present in the clinic, other than the dental curing lamp.

Through the observational studies, working information (e.g. types of curing lamps, duration and frequency of use of a dental curing lamp or actual *"nasion-tooth"* distance[3]) were identified in students' perspectives and two working scenarios, e.g. typical and worst case scenario, were created by the data from the observations.

Instrumentation for the measurement

A Specbos 1211 UV (JETI Germany, S/N: 2010143) spectroradiometer was used to measure the spectral radiance (L_{BS}) of a dental curing lamp in the dental simulation clinic.

[3] Nasion means "a craniometric point where the top of the nose meets the ridge of the forehead". (Scientific Committee on Health Environmental and Emerging Risks, 2017)

Characteristics of the dental curing lamp

A LED type professional dental curing lamp, BA Optima 10 curing light (B.A International LTD, S/N: H12010470B), was used by the students. It is set in the wavelength range from 420 to 480 nm and the curing outputs are from 1000 to 1200 mW/cm^2. The peak wavelength measured by Specbos was 455 nm. The Dental School used two types of digital radiometers to regularly calibrate their lamps (Figure 6.1).

The curing lamp emission were evaluated in the lighting laboratory at Thebarton campus of the University of Adelaide as the initial assessment before the simulation experiments in the dental simulation clinic (Table 6.1).

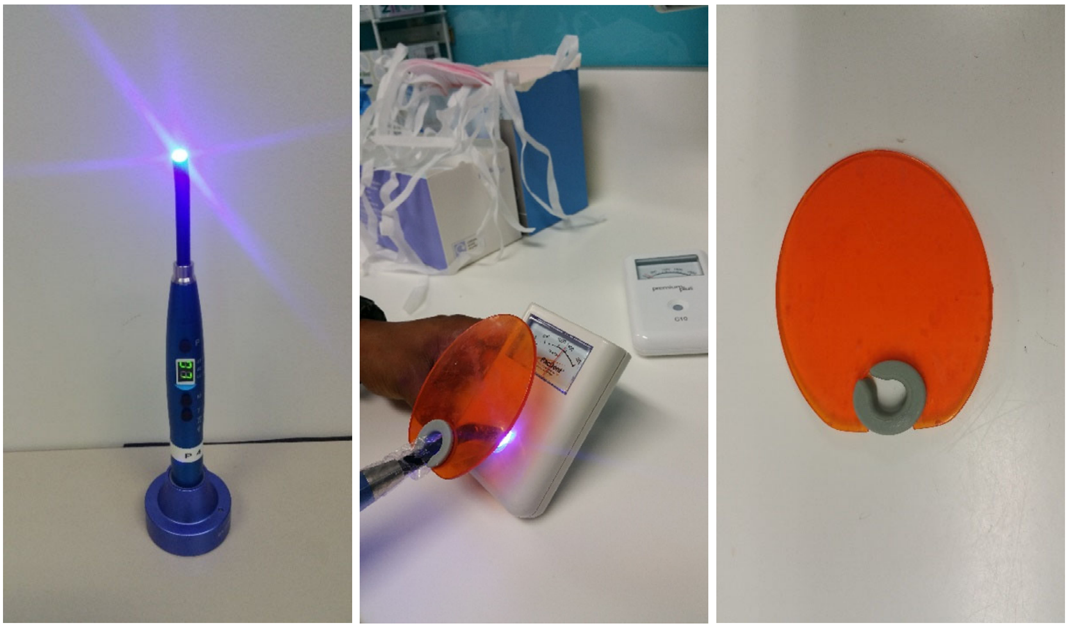

Figure 6.1 A dental curing lamp, digital radiometers and blue protective shield used in the dental simulation clinic

Table 6.1 Emission characteristics of a LED dental curing lamp

Measuring equipment	Measurement	BA Optima 10 curing light
Spectroradiometer Specbos 1211UV	Luminance [cd/m^2]	5966 – 6272
	Blue-weighted radiance L_B [W/m^{2}sr]	104.5 – 114.5

6.4 RESULTS

6.4.1 Field observational studies

General information about the teaching program in the simulation clinic

The average time was 3 hours per class in the simulation clinic and all students basically wore clear safety glasses, gloves, masks and lab coats according to the safety requirements of the university. Working distances from the treated false tooth of a mannequin mouth to the student eyes were around 15 to 30 cm and dependent on locations of teeth or students' personal behaviour and anthropometric measures (Figure 6.2). Angles from a curing lamp to student eyes also differed depending on the locations of teeth being treated. Dental curing lamps used in the clinic were typically set to be on for 20 sec, (range options: 1 to 40 sec) and the distance between a treated tooth and the curing lamp was 1-2 mm. Frequency of use of the curing lamp varied according to the treated tooth and students generally gazed at the tooth an average of 3 times per treatment, for 2 to 3 sec., while using a curing lamp. No students gazed at the tooth under treatment for the whole curing time (set-up 20 sec).

Figure 6.2 General conditions for the measurements in the dental simulation clinic

Based on the observational information above, estimated exposure durations for the second year dental students were created to use for the experimental calculations in this research. Table 6.2 is the potential/possible exposure durations of the students per one 3-hour class in terms of typical and worst case scenario. The estimated exposure duration for a dental student is typically 12 sec and the worst case estimate is 36 sec.

Table 6.2 Estimated case scenarios for second year dental students based on the observations

	Frequency /one curing	**Exposure duration (s)/one curing**	**Exposure duration (s)**
Typical case (2 teeth treatment)	2	3	**12**
Worst case (4 teeth treatment)	3	3	**36**

- Calculation for typical case: 2 teeth-treated × 2 times checking × 3 sec gazing = 12 sec
- Calculation for worst case: 4 teeth-treated × 3 times checking × 3 sec gazing = 36 sec

6.4.2 Exposure assessment simulation

Figure 6.3 shows the measurement points of the mannequin teeth by targets and angles, and the measurement locations for the curing lamp. The L_{BS} were measured at various points within 0.1 radian (6 degrees) alongside the lamp as per ICNIRP guidance (T1 to T4 on Figure 6.3) and at various angles in the fixed targets (A1 to A6 on Figure 6.3). The measurement distance was 25 cm and it was determined through the average of working distances of the dental students during the observations. One point for targeting were measured at least 5 times and the average levels of the L_{BS} were calculated in Table 6.3.

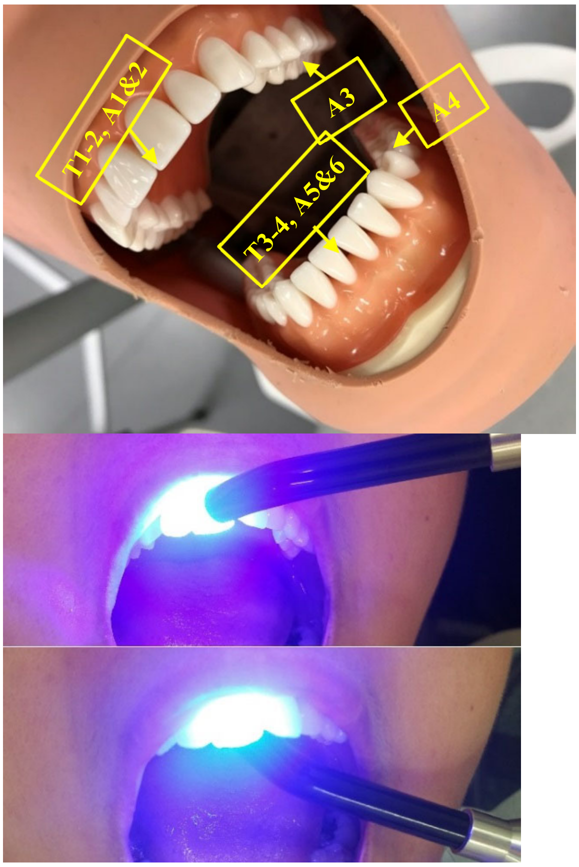

Figure 6.3 (a) Targets by targets (T1 to T6) and angles (A1 to A6), and (b) directions (top right: indirect, bottom right: direct)

Table 6.3 presents the outcomes from the simulations with the LED dental curing lamp using the estimated exposure durations. According to Labrie et al.'s study (2011), the potential risk of the direct exposure from the part of light emission of a dental curing lamp to the eyes can be higher than the indirect exposure. However, in the simulation experiments in this study, the both levels of the L_{BS} varied depending on locations and angles between treated teeth and the dental curing lamp.

Table 6.3 The effective blue weighted radiances (L_Bs) and the daily estimated effective radiance doses (D_Bs) for dental students by direction.

Exposure Direction	**Target**	**Range of L_B** (W/m^{2}sr)	**D_B/class** (J/m^{2}sr)	
			Typical case (12s/class)	Worst case (36s/class)
Indirect	T1	36.5 - 196.3	438 - 2355	1316 - 7066
	T3	117.5 - 194.5	1,410 - 2334	4230 -7002
	A2	3.2 - 123.6	38 - 1483	115 – 4449
	A3	0.6 - 175.8	7 - 2109	23 – 6328
	A4	0.6 - 187.3	7 - 2247	23 – 6742
	A6	10.9 - 51.1	131 - 614	394 – 1842
Direct	T2	13.6 - 46.8	163 - 561	490 – 1685
	T4	20.5 - 117.4	247 - 1408	741 – 4226
	A1	2.8 - 137.2	33 - 1646	101 – 4939
	A5	2.1 - 196.4	26 - 2356	78 - 7070

The range of the measured radiances (L_Bs) at 6 degrees were from 0.65 to 196 W/m^{2}sr for indirect targeting and from 2.16 to 196 W/m^{2}sr for direct targeting respectively. The estimated radiance doses (D_Bs) were 7 to 2356 J/m^{2}sr for the typical case scenario and 23 to 7070 J/m^{2}sr for the worst case scenario. The highest L_B that was able to be measured by the Specbos during initial experimentation with the mannequin mouth was 212 W/m^{2}sr which would mean, for the worst case scenario, the estimated D_B would be 7632 J/m^{2}sr. In terms of L_Bs the results of the direction of the exposure were not much different.

When comparing with the ICNIRP Guidelines, all results of the D_Bs calculated by the estimated exposure durations did not exceed the limit (10^6 J/m^{2}sr) during 8 hours per day even if the levels of some L_B exceeded the radiance limit (100 W/m^2sr).

6.5 DISCUSSION

In accordance with other research, the L_Bs differed depending on targets and angles of the teeth, ranging from 0.65 to 196 W/m^2sr (Table 6.3), with the highest L_B was greater than 212 W/m^2sr (the limit of the spectroradiometer). Thus, the radiance values assessed potential for overexposure to blue light from a dental curing lamp during dental classes may be higher than those measured in this research.

Unlike Labrie et al.'s study (2011), there were no significant differences between direct and indirect exposure to the curing lamp probably because in direct exposure, the teeth blocked light from the curing lamp. Depending on where/how the students use the lamp, the risks will vary.

Blue-light protective glasses can be effective in minimizing exposure but were not typically worn in the courses. Shielding around the lamp body was of limited effectiveness in practice, as L_B values in the visual field showed wide variability, depending on location of the tooth and angle of the curing lamp. Values often exceeded the radiance limit of 100 W/m^2sr (ICNIRP 2013). Bruzell et al. (2007) reported that lack of eye protection could occur through protective glasses or shields with poor quality while using dental curing lamps but there are no current regulations regarding blue light transmittance for the protective equipment. More information on standards for protecting eyes from the blue light exposure is needed.

6.6 CONCLUSIONS AND RECOMMENDATIONS

Although the effective blue light radiance doses (D_Bs) did not exceed the limit of the ICNIRP guidelines within the acceptable exposure duration per day, values of the effective blue light radiances (L_Bs) often exceeded the radiance limit of 100 W/m^2sr, close to the LED unit of a dental curing lamp and if the exposure duration exceeds 10,000 sec. It is also important to note that working conditions in a public hospital or in a private clinic ward/outpatient could be substantially different from those studied here, due to the more limited available space. Furthermore, paramedical and technical staff, not present in a dental simulation clinic but largely present in medical settings, should be considered for risk assessment.

It is recommended that blue-light protective glasses be worn by students and professionals, and that techniques to minimise exposure to this type of light be taught. New types of LED units (e.g. colour, shielding) for the dental curing lamp should be also considered. Since the radiation beam is filtered by the protective shield or safety glasses, it is difficult for the student to verify the exact position on the tooth surface as the blue light is being blocked (See Figure 6.4). Consideration could be given to the use of an alternate colour co-annular light source for teaching purposes, if not for more general use. Figure 6.5 illustrates the problem of a blue source becoming less visible with blue blocking lenses. A red co-annular source would not be blocked.

Training should include more detailed information on the blue light hazard, as anecdotally students are casually informed by the supervisors, rather than having information in standard operating procedures or course materials. Epidemiological studies into the prevalence of eye related damage of dental practitioners and more information regarding exposure time activity patterns in the occupational visual field should be considered in future studies.

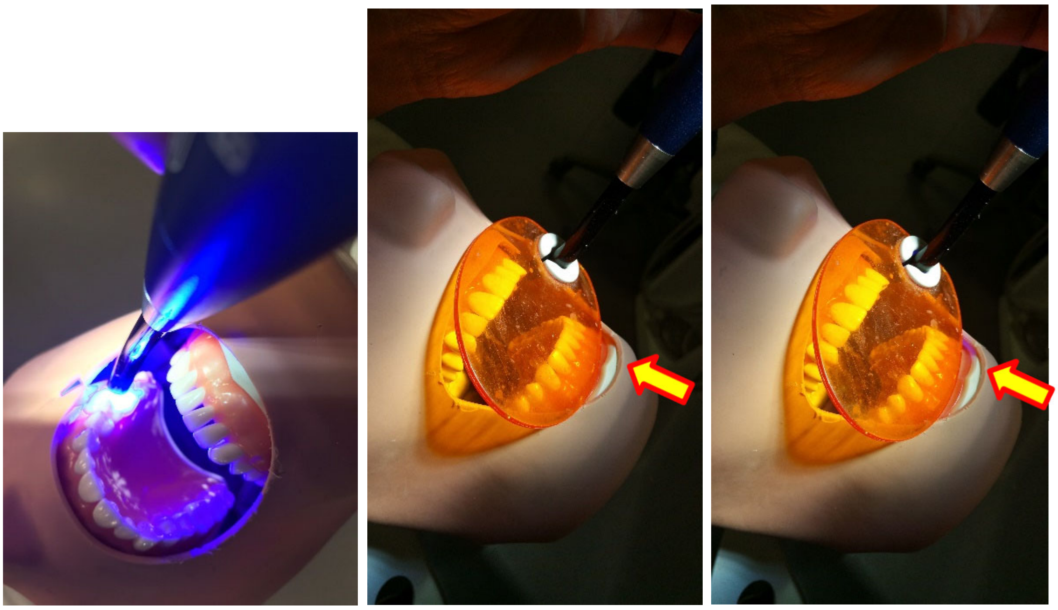

Figure 6.4 Comparison with a dental curing lamp on (left), a lamp on using a blue protective shield (centre) and off using a blue protective shield (right)

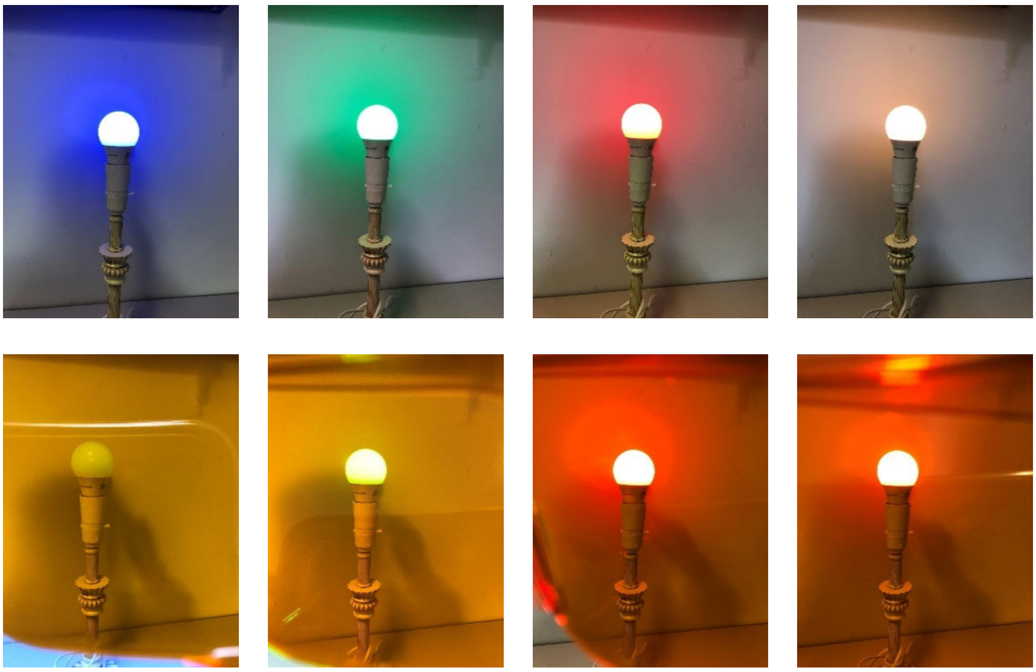

Figure 6.5 Colour distinctions with/without blue light safety glasses (Light colours from the top left to the top right: Blue, Red, Green, Yellow), (Filtered colours, using blue light safety glasses, from the bottom left to the bottom right), LED light source: MortBay Globes B22 2.8W LED, dimmable, colour changing RGB light. Safety glasses: UVEX S0360S

Chapter 7: General Discussion

This chapter *is an integration of research findings* following an occupational hygiene theme. A case study approach was used to explore this complex area, and commonalties are described.

The main findings are discussed in the context of available literature, and "work, worker, workplace" risk factors. In respect of the case studies, it will be argued that exposures are generally low, according to current knowledge, except in some specific instances. Finally, the strengths and limitations of the methodology are described

7.1 NOVELTY OF THE RESEARCH

This research utilised three novel approaches aimed at better understanding and measuring exposures, as well as informing professional practice.

Firstly, in Chapter 2 the *multidisciplinary and diverse* literature on the photochemical blue light hazard was reviewed using an occupational hygiene narrative - health hazard appraisal, exposure assessment and control.

Secondly, in the three case studies described in Chapters 4-6, the measurement of blue light was conducted in the *occupational visual field*. The exposure to blue light sources was characterised by a *combination of radiance measurement and time activity patterns*.

Finally, and in recognition of the high cost and complexity of blue light exposure assessment, *low-cost approaches to photometry and radiometry* were explored using smartphones and associated apps (see Appendices).

7.2 MAIN FINDINGS CONSIDERED WITH RESPECT TO "WORK/WORKER/WORKPLACE" RISK FACTORS

Based on the review in Chapter 2, the practical assessment of the photochemical blue light hazard does not figure prominently in the occupational hygiene literature. Only a few papers have been published and these have been in last 5-10 years. The focus has been on the blue-weighted radiance/irradiance exposure of specific workers who use or are exposed to blue light sources, such as medical professionals, nail technicians, performers or welders (Bonner et al., 2017; Dowdy & Sayre, 2013; Pinto et al. 2016; Price et al. 2016). There is no published study concerning the occupational risk of blue light exposure in Australia.

In addition, over the last ten years of the Annals of Occupational Hygiene/Work Exposures and Health, there have been only two papers dealing with the issue of photochemical blue light from arc welding (Nakashima, Takahashi, Fujii & Okuno, 2017; Okuno, Ojima & Saito, 2009). The Journal of Occupational and Environmental Hygiene only had four papers which were associated with the blue light exposure in medical fields and horticultural farms (Wu & Lefsrud, 2018; Price et al., 2016; Pinto et al., 2015; Bruzell et al., 2007). Similarly, in the related Ergonomics or Occupational Medicine journals, there is a shortage of literature on blue light hazards (see Chapter 2).

The reasons for a shortage of information in the occupational hygiene literature may be related to the cost of the instrumentation for blue light weighted radiance measurement, assessment being technically difficult and the overlapping of this field with ergonomics. In addition, there are many different types of artificial light sources with various designs, powers or colours as well as diverse lighting environments in occupational settings.

There are uncertainties regarding the proper risk assessment of blue light exposure and associated retinal damage, due to the highly directional exposure and limited information on dose-response.

Three case studies were undertaken to determine the exposure, with specific reference to occupational visual fields and time activity patterns.

Using observational information in the selected workplaces and product information provided by manufacturers, the exposures of three different types of blue light sources used in workplaces were evaluated in the case studies.

Key findings from observations and simulation experiments are described in terms of the ***work/worker/workplace*** *framework* (Table 7.1) and the exposure assessments of blue light sources are discussed in the framework.

Table 7.1 Summary of the exposure scenarios from the case studies

	work	worker	workplace
Case study 1 *Nail technicians* using a nail curing lamp	Fixed position blue light source for task which can be a short distance	Limited education Limited awareness of risk Young age group	No other significant blue light sources in shop environment
Case study 1 *Presenters* who use a video recording studio in the University	Direct and indirect lighting according to requirements.	Educated, but unaware of risk	No other significant light sources
Case study 3 *Dental students* using dental curing lamps	Handheld light source, direct and reflected lighting	Educated, but unaware of risk Young age group	One overhead white light source

Through preliminary feasibility studies discussed with lighting and health and safety professionals, three different types of blue light source and workplaces were selected. These are consistent with the blue light sources classified by the ACGIH (see Table 1.2). The major considerations for selecting these workplaces for assessment were convenience (easy to access) and ability to observe procedures (see more details in Chapter 3).

7.2.1 With respect to "work"

Case study 1 – nail salons with nail curing lamps

The design of UV nail lamp openings is such that they face the customers and thus theoretically they may have higher exposures than nail technicians during the brief curing process (see Figure 4.1). However, most customers only visit nail salons periodically (e.g. monthly), while nail technicians have many customers to attend to daily (Nail magazine, 2016). Hence, the duration of workers' exposure to UV nail lamps would greatly exceed that of a typical customer's exposure (e.g. Estimated viewing durations in the worst case were 900 seconds for a customer per month and 2700 seconds for a nail technician per day).

The stronger powered (36W) LED nail lamp showed higher radiances than the low powered (18W) lamp. The levels of L_{BS} and D_{BS} were well below the current limits, even in the worst case, based on exposure time and tasks. Interestingly, due to the locations of installed LED units and the non-shielded opening design of the 18W LED nail curing lamp, both sides at the corners showed higher values of L_{BS} than at the centre (Figure 4.5 & Table 4.4). This shows that the amount of exposure can differ depending on visual fixation.

The observed angle from the workers'/customers' eyes to the opening of the lamps was around 45 degrees, all nail curing lamps being situated on the working desks. The likely worst case scenario is when nail technicians have longer exposure times when making longer false nails (artistic nail design).

Dowdy & Sayre (2013) measured the UV and blue light exposure to the eyes from six UV nail lamps. Of the six nail lamps, LED sources with a peak emission wavelength of around 400 nm were almost double the intensity than the fluorescent sources with a peak emission wavelength of around 370 nm. As there were various opening designs of the nail lamp units, these openings were removed and the E_{BS} were measured at 20 cm. (as the worst case distance from IEC 62471:2006) and at the angle of 0° (direct) and 45°. Their outcomes did not exceed the limit of the spectral irradiances (E_{BS}), 1 W/m^2, and the study concluded that there was no photochemical blue light risk from the UV nail lamps, except for one fluorescent UV nail lamp which showed a slight risk to the aphakic eye.

Overall, the most significant "work" risk factor is the exposure time, but exposures may increase if the lamp covershield is removed.

Case study 2 – video production studio

In case study 2 (Chapter 5), blue-rich white LEDs were used in a video recording studio of the University (Figure 5.2). The light sources in the studio were mostly white LEDs excepting fluorescent ceiling lamps (see Figure 5.1 & 5.2). The intensity of the LEDs was controlled in a studio control room and two different types of diffusers were used for panel LEDs; a type of fabric and plastic (Figure 5.2). The panel LEDs with fabric diffusers showed lower L_Bs than the LEDs with plastic diffusers (Table 5.4).

The amount of exposure to these sources was shown to depend on viewing directions and exposure durations of workers. Generally, the background lights in a video recording studio (e.g. over 600 lx) were brighter than other typical offices or industrial areas. All light sources in the studio were installed on the ceiling and towards the centre of the stage and did not directly face towards the presenter's eyes as they looked straight ahead. However, the eyes and the head of a presenter move continuously and thus can have diverse working positions during recording. Using three exposure scenarios, the time activity patterns were estimated for a 1-hour recording duration (Table 5.3). In exposure scenario 3, when two presenters are sitting across from each other under front light sources, the two panel LEDs (light source numbers ② & ③ in Figure 5.2) were always located in their OVFs – one for each panel LED, and both people were expected to be more highly exposed to intense bright light sources than in the other two scenarios (see in Table 5.7 & Figure 5.7, 5.8 & 5.9). According to the results of measurements in the studio, the L_Bs of spotlights exceeded 100 W/m^2sr and the contrast between the illuminated spot and dark background studio was very high and discomfort glare could be induced. Despite the L_B of the spotlight exceeding the guidance L_B, the total level of the D_B in scenario 2 (one presenter under two LED spotlights) using estimated viewing targets and durations over a 1-hour recording, showed similar levels with the D_B of the scenario 1 (one presenter under seven general panel LEDs). This is because of the eye/head movement of a presenter, and one or more front light sources (4 LED panels and 2 spotlight LEDs) were included in the OVF.

The available hours for booking the video recording studio were from 1 hour up to 3 hours a day. Based on a simple calculation multiplying the 1-hour data by 3 (maximum 3-hour recording session), the worst D_{BS} of a presenter(s) were 69,363 J/m^{2}sr for scenario 1, 35,820 J/m^{2}sr for scenario 2 and 72,753 J/m^{2}sr for the right presenter in scenario 3, and all D_{BS} did not exceed the limit, 10^6 J/m^{2}sr.

Hietanen and Hoikkala (1990) measured photoflood metal halides and halogens lamps in TV studios and theatres and the lamps measured did exceed the limit of L_B with permissible exposure durations (t_{max}) from less than 1 minute up to 3 hours. Bonner et al. (2012) assessed personal exposures to artificial light sources on large-scale stages. Using five simplifying assumptions (e.g. closest distances, direct viewing, 8-hour exposure duration, unrestricted visual field and blue light exposure limit value (ELV) of E_B (1 W/m^2)) and hazard ratios, the personal exposures in large venues were practically assessed. Blue LEDs and white LEDs on a stage exceeded the limit of E_B, but the risk of blue light exposure was considered very low, except when a performer or crew member looks directly up at the blue light sources.

Overall, personal exposure to blue light in the video production studio depends on exposure time and the choice of light used for a particular form of presentation, e.g. preferential use of spotlights.

Case study 3 – dental simulation clinic

In case study 3 (Chapter 6), there were two blue light sources used in the dental simulation clinic: dental curing lamps and overhead LEDs (Figure 6.1 & 6.2). The luminance of the overhead LED was over 665,000 cd/m^2. However, case study 3 only focused on the potential exposure to a dental curing lamp of dental students and the exposure to the overhead LED was not really considered in the OVF. Patients may be directly exposed to blue light from the overhead lamp during treatments and thus appropriate blue light blocking safety eye glasses for the patients are recommended.

A dental curing lamp emits intense blue light and is used for polymerizing dental resin-based materials. Second year dental students receive their practical training in the dental simulation clinic for 3 hours per class and around 160 hours per one semester and make frequent use of handheld curing lamps in their practical work.

The working distances were quite close, from 15 to 30 cm, and the average angle from the teeth being treated to students' eyes was 45 degrees (Figure 6.2). However, both distances and angles varied depending on the position of the treatment. The potential exposure duration of a typical and the worst-case scenario estimated by the observations were 108 sec and 240 sec during 3-hour classes respectively (Table 6.2). The levels of L_Bs differed depending on targets, angles and the position of teeth, ranging from 0.6 to 196 W/m^{2}sr (Table 6.3). The estimated D_Bs were 7 to 2,356 J/m^{2}sr and did not exceed the limit. Even the worst D_B (7,632 J/m^{2}sr) estimated by the highest L_B (212 W/m^{2}sr) did not exceed the limit. However, the centre and the edge of a curing lamp were beyond the limits of the spectroradiometer, therefore the actual L_B would be higher than the maximum measured. According to Labrie et al. (2011), the partial direct exposure from the dental curing lamp to the eyes when used from behind the teeth is higher than the indirect exposure from reflection when the lamp is used towards the tooth (see Figure 6.3 (b)). However, in the actual simulation experiments in Chapter 6, the L_Bs depended on targets and angles between treated teeth and the curing lamp (see Table 6.3).

Overall, the exposure in the dental simulation clinic depends on frequency and duration of curing, angle of work and reflective surfaces, and the adequacy of the blue light shielding of the handheld source.

In conclusion, the ***blue-weighted spectral radiance dose (D_B) depends on worker's OVFs, direct viewing angles, source intensity and time/activity patterns*** *of the blue light exposure.*

7.2.2 With respect to "worker"

Workers of young age may be more vulnerable when exposed to health hazards including blue light sources in workplaces. Due to inexperience and being less likely of awareness of occupational health and safety issues, young workers aged 15 – 24 years were at higher risk of workplace accidents than adult groups (Barnetson & Foster, 2012; Breslin et al., 2019; Jennifer, Purewal, Macpherson, & Pike, 2018). According to occupational health and safety data, young workers under 25 years of age are statistically more at risk of occupational injury than older workers (Breslin & Smith, 2005; Holte & Kjestveit, 2012).

With respect to issues related to eyes, anatomically there is a 20 % higher transparency of the eye's crystalline lens for young people in their 20s compared with adults in their 50s (Zak & Ostrovsky, 2012). In other words, more blue light can reach the retina of young workers than older workers.

Similarly, ***new workers*** unaccustomed to their new tasks, may be more vulnerable to work related eye injuries (WREI) from blue light exposure. According to Barnetson & Foster's study (2012), new and young workers were more careless and neglectful of workplace safety, and could be more at risk of WREIs. In fact, work-related eye injuries were statistically more likely to occur in younger workers and workers with the performance of an unfamiliar task (Chen, Fong, Lin, Chang, & Chan, 2009). Serinken et al. (2013) reported that the patients with WREIs were more likely to be between 25 to 34 years of age and the major causes of WREIs were inexperience and unfamiliarity with working requirements, carelessness and impatience. Ho et al. (2008) conducted a case-control study to find the risk factors for occupational eye injuries. They found that workers temporarily employed and those with less education (no more than 10 years of education) were at higher risk of eye injuries.

Therefore, ***young workers*** *with greater transparency of the eye and* ***new workers*** *with unfamiliar tasks are likely to have less awareness about safety issues and may be more vulnerable to blue light exposure.*

In particular, ***outdoor workers*** with long-term solar radiation exposure during working hours showed a higher risk of retinal damage than indoor workers (Bressler et al., 1989; Modenese & Gobba, 2019). The sun is the most powerful blue light source in nature. Outdoor workers in fisheries, construction sites or farming are regularly exposed to the sun and showed increased macular degeneration (Modenese, Korpinen & Gobba, 2018). Another case-control study also reported that there was a high correlation between past sunlight exposure (less than 8 hours outdoor work a day) and early AMD, an initial stage of vision loss. Outdoor working was also associated with the development of late AMD; an advanced stage which can lead to permanent vision loss (Schick et al., 2016). In contrast, Zhou et al. (2018) concluded that sunlight exposure did not seem likely to increase risk of AMD based on current peer-reviewed studies. Park et al. (2014) also reported that both early and late AMD were not found to be associated with sun exposure, although they added that the association between sun exposure and AMD was evaluated using a single question regarding estimated average hours of sunlight exposure a day. They stated that further studies with thorough evaluation of sun exposure were needed.

However, regardless of age, work experience or outdoor work, ***workers who have had eye surgery*** such as lentectomy or corneal cataract surgery may be more sensitive to the effects of blue light (Algvere, Marshall, & Seregard, 2006: Connell et al., 2009; Ide et al., 2015; Wu, et al., 2006). The ocular media such as cornea and crystalline lens can filter most electromagnetic radiation and transmit certain wavelengths ranged from 400 nm to 700 nm (Cuthbertson et al. 2009). In particular, the human crystalline lens turns yellow with age and can reduce the amount of transmission of short wavelengths between 400 nm and 500 nm. Patients who have had surgery to remove the crystalline lens and have it replaced with an intraocular lens (IOL) can be more highly exposed to blue light than persons who have their own crystalline lens (Cuthbertson et al. 2009; Mainster & Turner, 2010). Cowan (1992) reported that during surgery, patients could have intraoperative blue light exposure from the operating microscope, the indirect ophthalmoscope, and the endoilluminator in the operating room and could be at risk of photochemical damage during the eye operation. For this, blue filtering IOLs can be used as the viable alternatives to the patients with cataract surgery. There are also arguments against use of the blue filtering IOLs due to disadvantages such as dimming of vision and potential sleep disorder from blocking short wavelengths (Cuthbertson et al. 2009; Mainster & Turner, 2010).

Based on these susceptibility factors, three different types of workers who can be often exposed to blue light sources were considered in the three case studies (Chapters 4 to 6). Nail technicians observed in Chapter 4 were mostly young Vietnamese and Chinese females who do not speak English as their first language and did not appear to use any eye protective equipment for reducing the exposure to nail curing lamps. They had short working distances of around 30 cm from their eyes to the nail curing lamp and were unaware of the risk of the exposure to blue light from a nail curing lamp. Presenters who use the video recording studio in Chapter 5 were academic lecturers or University students of different age groups, thus more highly educated. The studio light sources (generally white LEDs) were installed in the ceiling and illuminated the presenters. The working distances from the light sources to the eyes of the presenters were less than 3 m depending on the presenters' viewing directions. There were no safety considerations concerning the exposure to lighting/blue light. Dental students in Chapter 6 were mostly young (between late teens and early 20s) and reasonably educated, but perhaps with insufficient understanding of the blue light hazard with intense blue light source.

7.2.3 With respect to "workplace"

The following are three examples of workplaces that have fixed lighting that may be potentially significant blue light sources.

Firstly, ***deliberately installed blue light sources*** for special effects such as in jewellery shops, display rooms or art galleries can be considered.

In order to create comfortable atmospheres and to influence customers' purchasing decisions, various blue light sources can be used for displaying items. In case of jewellery shops, different coloured and sized light sources are used to display various spectacular gems. In the case of art galleries, according to the type of artwork, various types of light sources can be used to highlight the artwork.

Secondly, inappropriate ***blue light sources that have been installed in workplaces*** need to be considered. It is important to use the right light sources in the workplace. For example, a metal halide lamp with a high level of L_B is not suitable for a desk lamp. In Appendix A1, a 70W metal halide lamp did exceed the limit of L_B and a worker can be at high risk of exposure to blue light if the metal halide lamp is directed straight at the worker's face (or in the worker's OVF).

Finally, workplaces with ***stray and unwanted reflected light*** also need to be considered.

The power of reflected sunlight can be found in the history of Archimedes of Syracuse, who allegedly destroyed Roman ships with fire using the giant mirrors to concentrate sunlight in 214 - 212 B.C. (Simms, 1991). Depending on times, seasons and weather conditions, the amount of exposure to reflected sunlight can differ. It mainly appears in outdoor workplaces such as construction sites, fishery or farming industries, but some indoor workers can also be affected by reflected sunlight from windows (Figure 7.1). To illustrate, in the Chesapeake Bay watermen study in 1989, fishermen exposed to reflected bright sun light from the water on a daily basis, showed a higher rate of early AMD believed to be related to blue light exposure (Bressler et al., 1989). There is also the intense light reflecting off snow that can have significant effects on the eyes (Yilmaz, Yildiz & Yilmaz, 2008). Architectural design can be also related to the exposure to reflected sunlight. The potential power of reflected light was reported in the case of a vehicle dashboard being melted by the reflected and concentrated sunlight from a tall skyscraper building designed in a concave shape (Figure 7.2) (Mullin, 2014). In fact, the L_Bs of reflected light from the surface of a metal reflector in the 36W nail curing lamp showed much higher results compared to other internal bases such as white/grey/black papers (Chapter 4).

Appendix C shows simple and clear results associated with the risk of exposure to reflected blue light. An example of reflected exposure is seen from the experiment with clear safety glasses, which showed two times higher levels of the L_Bs from the LED dental curing lamp and the 18W LED nail curing lamp, than their original L_Bs (without using the safety glasses) (Table C.2).

Figure 7.1 Sun light reflecting from the surface of the sea (top) and glass walls (bottom)

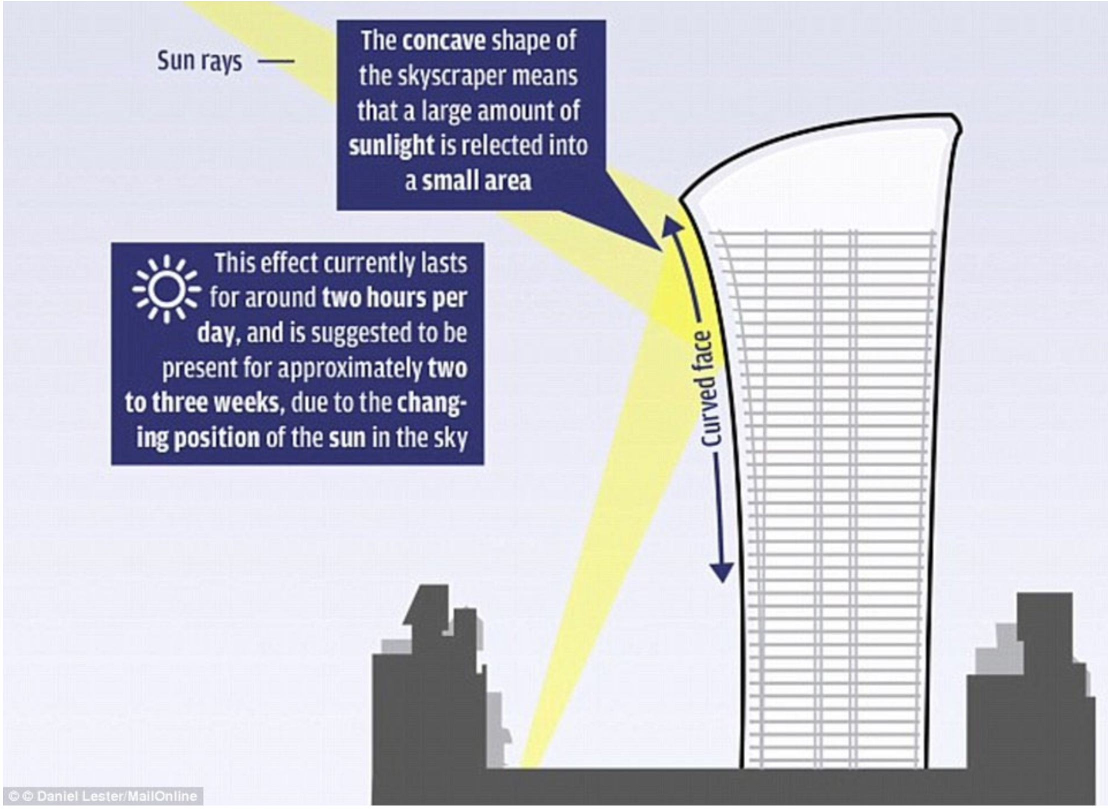

Figure 7.2 Design of the skyscraper building in London
(Photo by Daily Mail, website: https://www.dailymail.co.uk/news/article-2786723/London-skyscraper-Walkie-Talkie-melted-cars-reflecting-sunlight-fitted-shading.html)

7.3 LOW COST METHODOLOGICAL APPROACHES

7.3.1 Practical considerations (mobile phones) referring to Appendix B

In Appendix B, use of smartphone applications (apps) in the assessment of the occupational lighting environment was explored through three simulation experiments.

Before the actual field observations for lighting surveys in workplaces, occupational hygienists can obtain preliminary information from various ways such as photos and floorplans. In particular, 3-Dimensional (3D) images can provide spatial information about light source locations in the workplace. However, a 3D camera is not commonly used due to cost or compatibility issues where 3D images cannot be viewed in some programs. For this, the "Google Street View (GSV)" application offered for free on Google Maps, was used in Appendix B1. Using the GSV app on the smartphone, initial lighting information can be obtained from 3D images with real time geographic information and shared with other practitioners at the same time. Figure B1.1 shows the 3D image of the video recording studio taken by the GSV on Google Maps, a photo-sharing website. Through this image, spatio-temporal information about lighting environments could be found (Figure B1.1). Even if there are problems such as taking a long time for making and uploading 3D images, spatial distortion images or security concerns (Table B1.1), the GSV app could show useful information which a 2D image or a floorplan could not, and thus it could be useful for initial lighting observations.

In Appendix B2, light meter apps were used to measure the values of illuminance in occupational settings as an alternative for using lux meters. Vertical reference illuminance values from the professional lux meter were 148 lx at 1.5m below a cool-white downlight LED and 125 lx at 1.5m below under a warm-white downlight LED and the illuminance values from the light meter apps varied from 91 lx to 296 lx. On average, the illuminance values under a cool-white LED were higher than under warm-white LED, however, comparative results varied significantly, whether under cool- or warm-white LEDs (Figure B2.3). Interestingly, the iPhone and iPad installed iOS operating system have two light sensors in front and rear camera respectively and can detect illuminance with both sensors. However, the front light sensor produced significantly lower values than the rear sensor for iPhones and iPads, in a mobile device used.

In order to assess the illuminance values from multiple angles, two luminaires each with two parallel fluorescent tubes fitted, in an office ceiling were used. iPhones' and iPads' front sensor showed lower, but variable illuminance values than the rear sensors. The illuminance values based on colour temperature in the multiple angles from the mixed lighting conditions did not show a large difference. Unlike the results under vertical down-lighting LEDs, illuminance values from multiple angles were more variable for all mobile devices. Under the non-vertical lighting condition using only the fluorescent lamps, all mobile apps showed significantly lower illuminance levels than the lux meter used (Figure B2.4). Under the same reference illuminance, 320 lx, each app at the same location showed different results compared to the reference (Figure B2.5). With all illuminance values, Galaxy Note 3 showed the lowest range of the deviation and iPhone 4s rear camera sensor showed the highest range of deviation compared the reference illuminance values (Table B2.3).

In comparison with other studies that have only measured the vertical illuminance of light meter apps (Cerqueira et al, 2018; Goldschmidt & Pittner, 2016), this study considered illuminance values at various angles and the intensities of the illuminance from side directions were lower than vertical illuminances (see Figure B2.4). There are several portable dome-shaped diffuser attachments for mobile phones for measuring illuminance (Goldschmidt & Pittner, 2016), but this study only focused on the use of mobile light meter apps using a flat screen and did not assess other attachment devices.

Smartphone light meter apps are handy for measuring illuminance of light in occupational settings. However, they are more useful for measurement in the vertical direction as there may be large variations with professional lux meters commonly used by occupational hygienists and ergonomists, which take into account the angled/cosine correction

7.3.2 Blue-weighted luminance referring to Appendix A2 & B3

Okuno (1988) demonstrated that a luminance meter can be used instead of a spectroradiometer when suitable colour filters are attached to the luminance meter. Based on his study, an additional study in Appendix A2 was conducted using one blue filter, to examine if it was possible that blue light sources could be discerned using the luminance meter in combination with a blue filter (Figure A2.1).

When comparing emission of blue light between the L_B and the blue L_V of an RGB LED globe, the proportion of emission of blue light results were higher for the blue colour range than the red colour range (Table A2.3). This suggests that the blue L_V could be used to discriminate blue light sources from various different types of light sources before going on with further experiments using general light sources such as cool-white LED globe or halogen globe. In particular, a 42W halogen showed a high L_B, 92 $W/^2sr$, but the proportion of emission was only 8.9 % compared to the proportion of a 13W warmwhite LED globe or 10W coolwhite LED globe which showed lower levels of L_Bs than the halogen (Table A2.4). Based on the emission proportion results in Table A2.4, the 42W halogen was the weakest of the blue light sources, but it was the second highest blue-weighted radiance source. It was not possible to compare luminance and radiance values as was done in Okuno's study which used six different coloured filters.

In addition, the transmittance of the blue filter (HOYA, B-440) used in this study depended on wavelength spectrum (See Figure A2.4) and also the intensity of various light sources varied depending on their wavelength spectra.

Using the blue filter on a smartphone light sensor, the blue light hazard function (BLHF) illuminance was measured in Appendix B3. The illuminance values from all devices with a blue filter were low, typically 0 to 5 lx (Table B3.1).

On the whole, the BLHF illuminances from mobile apps and the lux meter with a blue filter, were almost 100 times lower than the values without the filter. This problematic for moderate sources but there is some potential for determining the blue light hazard from exposure to very bright blue light sources.

7.4 STRENGTHS AND LIMITATIONS

Strengths

This research was the first to examine the blue-weighted spectral radiances (L_Bs) and the blue-weighted spectral radiance doses (D_Bs) in terms of actual time activity patterns and the occupational visual field

- Using the initial information (e.g. exposure distances, durations or angles of workers) collected from actual field-work observations in selected workplaces, potential exposure durations considering time activity patterns-observed were estimated to calculate the D_Bs within actual workers' OVFs.

The earlier studies using the ICNIRP guidelines only considered the levels of the L_B and compared their L_Bs to the limit from the guidelines, e.g. 100 W/m^{2}sr, t > 10,000 sec (ICNIRP, 2013; Pinto et al., 2015; O'Hagan, Khazova & Price et al., 2016). There are several research papers using ACGIH TLVs which show permissible exposure times (t_{max}) per day calculated by the L_Bs (Okuno, Saito & Ojima, 2002; Price et al., 2016). However, these outcomes (L_B or t_{max}) did not provide the actual integrated radiance dose for workers. This research focused on analysing the actual levels of the L_B and D_B of workers based on occupational hygiene perspectives; observations and simulation experiments, and thus, the outcomes could be used for stakeholders and occupational hygienists and ergonomists as an exposure assessment methodology for blue light in the workplace.

Limitations

- The Specbos 1211UV (spectroradiometer) used to measure the blue-weighted spectral radiance (L_B) had a limited range of the measurement of light sources and could not measure very intense light sources used in the simulation experiments, such as from the centre of the nail and dental curing lamps and LED spotlights. Thus, the actual blue weighted radiances of the intense light sources could be higher, in some cases, in the case studies.
- The amount of the blue light exposure was not investigated in actual working conditions. This is very difficult to do without a personal blue light sampler,

as it would entail a sensor at the eye position, or between the eyes, and continuous recording. Such a device is not yet commercially available.

Chapter 8: General Conclusions and Recommendations

8.1 GENERAL CONCLUSIONS

Conclusions from the narrative literature review and three case studies can be briefly stated as follows:

- Blue light can damage the visual photoreceptors and lead to degenerative retinal diseases. The retinal photochemical damage from blue light exposure can be cumulative and irreversible. Workers who are exposed to very intense light sources, such as arc welding lamps or dental curing lamps, can be more at risk of retinal damage than other workers.
- Generally, aging is closely related to retinal photochemical injuries and long term exposure to blue light is a potential risk factor for macular degeneration.
- The assessment of blue light exposure is very complex and there are few systematic and epidemiological studies conducted from an occupational exposure perspective.
- Exposure assessment for a complex task requires more detailed time/activity assessment relative to direct and reflected blue light sources and assessment of the risk of exposure to blue light needs to consider the occupational visual field.
- Workers can have different OVFs and variable exposure durations.
- The levels of L_{BS} measured in the 3 case studies differed depending the subjects and their positions/angles relative to the blue light sources.
- Depending on where/how the workers use the blue light sources, the amount of blue light exposure can differ and thus, the potential risks will vary.

- All D_{BS} in three case studies did not exceed the limit of the spectral radiance dose, 10^6 W/m^{2}sr. However, the L_{BS} of LED spotlights and a dental curing lamp did exceed the radiance limit of 100 W/m^{2}sr.
- Blue-light filtered glasses or shields can be effective in minimizing exposure.
- The luminance meter with a blue filter may be used to identify blue light sources in the initial stage of a lighting survey.
- Smartphone applications such as light meter applications and Google Street View (GSV) may be useful for preliminary lighting survey and light meter applications, especially, may be used in place of a professional lux meter, if light sensors that can be installed in smartphones are further developed for superior photometric measurement.
- Owing to the potential variability of ocular exposures, e.g. viewing times, and radiances, epidemiological studies on populations exposed to significant blue light sources in the visual field should be conducted.

8.2 GENERAL RECOMMENDATIONS

Several recommendations can be considered for occupational professionals, workers, manufacturers and future researchers.

For occupational health professionals

Exposure assessment should be considered with respect to workers' time activity patterns and directionality of blue light sources with eye/head movements, and to this end, actual workers' individual occupational visual fields (OVFs) should be measured/observed.

For preliminary lighting surveys, mobile applications (e.g. smartphone light apps or Google Street View app) with low- or no-cost and photometry devices with a blue light filter may be feasible to adapt for use as an alternative to professional equipment However, they should be more fully developed to be put to practical use in the actual fieldwork assessments.

For workers

Workers should be made aware of intense blue light sources in the workplace. Where they are used as part of the work, they should receive specific training and the appropriate eye protection. This is especially important for young workers, who have higher transparency of the eye's crystalline lens than older workers and can be more exposed to blue light, and new workers who are less likely of awareness of occupational health and safety issues.

For manufacturers and designers

A nail curing lamp with a pull-down cover is highly recommended for blocking the emission of blue light from a nail lamp for workers. Multiple LED sources used in video recording studio (e.g. LED spotlight or white LEDs) need to be carefully designed and installed to minimise potential risks of blue light exposure.

More specific and detailed information related to classifications of their light sources and potential health effects from the exposure to blue light should be provided for all stakeholders.

A new type of a dental curing lamp with two different coloured monochromatic light sources could be used for training purpose in a dental school.

For visual science educational institutions and professional bodies

Professionals and professional bodies related to vision science need to provide specific training or professional development on the clinical investigation of persons who may be exposed to blue light.

For future researchers

Systematic and epidemiological studies are needed to provide further data on the risks of exposure to blue light in the workplace. The International Commission on Illumination (CIE) have recently stated that the standards regarding the exposure limits have not been based on human clinical trials and that claims that AMD can be induced by blue light exposure are "currently speculative and are not supported by the peer-reviewed literature" (CIE Board of Administration, 2019). More data from exposure assessments to various light sources are needed. Another aspect which should be considered is the occupational visual field for individual workers who have different tasks, working durations and certain working conditions.

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Appendices

The following appendices relate to certain experiments in support of the methodology used in the case studies (Chapters 4 to 6).

Appendix A describes experiments with light sources often found in workplaces. The assessment of blue light parameters is described, including the use of a luminance meter with a blue filter, as a low cost substitute for a radiometer. The approach can be related to all three case studies.

Appendix B describes some aspects of smartphone applications for lighting assessment. The Google Street View (GSV) app may be used for lighting surveys, and was used in Case study 2 (video production studio)

In addition, the applicability of smartphone light sensors for low cost and convenient evaluation of illuminance (including blue-weighted illuminance) is explored.

In Appendix C the performance of protective eye wear with respect to blue light is examined, in the context of Case study 3 (dental simulation suite).

Appendix A.

Assessment of blue light sources in the workplace

Assessment of the full extent of exposure to blue light is complex because of various lighting conditions and the many different types of blue light sources used in workplaces.

Most occupational health professionals are unfamiliar with the methodological issues in blue light exposure assessment.

The ICNIRP guidelines provide limits of exposure to blue light, but require an understanding of exposure durations and acceptance averaging angles in the visual field. In practice, there may be a number of uncertainties and variables to be addressed.

In order to appreciate this complexity and explore options for low cost assessment, a series of preliminary experiments was undertaken.

Appendix A consists of two parts:

A1. Preliminary experiments to measure spectral radiances (L_{BS}) of various light sources within the viewing angle

A2. Low cost equipment using a blue filter for measuring blue-weighted luminance

A1. Preliminary experiments assessing blue-weighted spectral radiances for some common light sources

Blue light exposure assessment requires the use of a radiometer, or preferably a spectroradiometer, rather than a photometer (lux or luminance meter) (ICNIRP, 2013). There is no simple or reliable conversion factor between photometric and radiometric quantities.

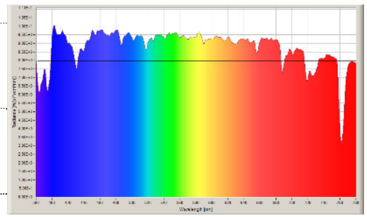
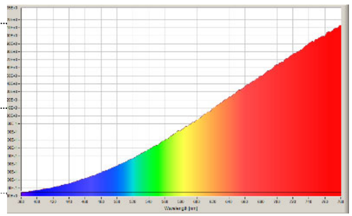
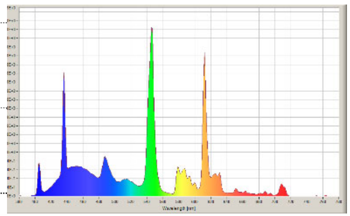
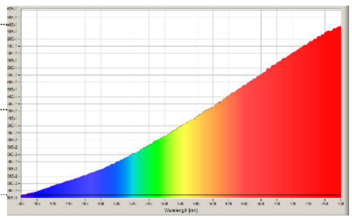
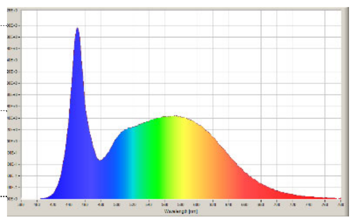
This appendix A1 describes the application of the ICNIRP guidelines (especially, the levels of L_{BS} considered by acceptance viewing angles within exposure duration) through the simplified preliminary experiments using blue light sources.

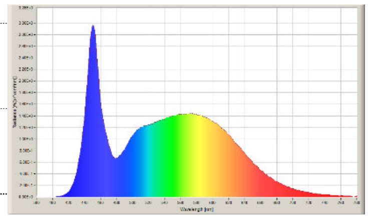
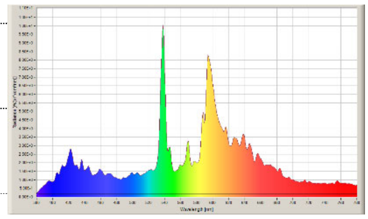
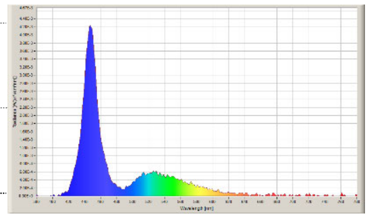
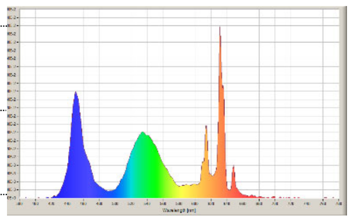
A1.1 Characteristics of general light sources in workplaces as initial experiments

From natural light source (blue sky) to various artificial light sources generally used in workplaces, the emissions of various light sources were evaluated as the initial assessments (Table A1.1). In addition to light sources for illumination, there were self-illuminating display screens, e.g. computer monitor and mobile phone screens, which are integral to the task. The spectral radiances are very low (0.09 W/m^2sr for computer monitor and 0.52 W/m^2sr for a mobile phone screen) even for completely white or blue screens at maximum brightness (Table A1.1).

Depending on types, colour temperatures and powers of light sources, the outputs of the wavelengths differed (Figure A1.1).

Table A1. 1 Emission characteristics of typical light sources used in workplaces

Light sources	Picture	Specbos values		Spectral output (centre targeted)
Blue sky (May 2018, Adelaide, Australia)		Luminance (cd/m^2)	682300	
		CCT (k)	5474	
		Spectral radiance (W/m^{2}sr)	3519	
		Blue-weighted radiance (W/m^{2}sr)	625.6	
Incandescent/ Philips 60W		Luminance (cd/m^2)	52330	
		CCT (k)	2614	
		Spectral radiance (W/m^{2}sr)	367	
		Blue-weighted radiance (W/m^{2}sr)	12.9	
CFL Osram 18W		Luminance (cd/m^2)	47070	
		CCT (k)	6533	
		Spectral radiance (W/m^{2}sr)	152	
		Blue-weighted radiance (W/m^{2}sr)	41.95	
Halogen Osram 40W		Luminance (cd/m^2)	6376	
		CCT (k)	2770	
		Spectral radiance (W/m^{2}sr)	43	
		Blue-weighted radiance (W/m^{2}sr)	1.84	
Metal halide Osram 70W warm-white		Luminance (cd/m^2)	225700	
		CCT (k)	3161	
		Spectral radiance (W/m^{2}sr)	805	
		Blue-weighted radiance (W/m^{2}sr)	112.3	

LED Philips 14W cool-daylight		Luminance (cd/m^2)	93040	
		CCT (k)	6038	
		Spectral radiance (W/m^{2}sr)	299	
		Blue-weighted radiance (W/m^{2}sr)	74.97	
LED Philips 13W warm-white		Luminance (cd/m^2)	135300	
		CCT (k)	3048	
		Spectral radiance (W/m^{2}sr)	413	
		Blue-weighted radiance (W/m^{2}sr)	42.29	
Acer LCD monitor (Model No. E1900HQ, blue screen background)		Luminance (cd/m^2)	26	
		CCT (k)	-	
		Spectral radiance (W/m^{2}sr)	0.16	
		Blue-weighted radiance (W/m^{2}sr)	0.09	
iPhone8 (white screen background, full bright mode)		Luminance (cd/m^2)	623	
		CCT (k)	6734	
		Spectral radiance (W/m^{2}sr)	2.01	
		Blue-weighted radiance (W/m^{2}sr)	0.52	

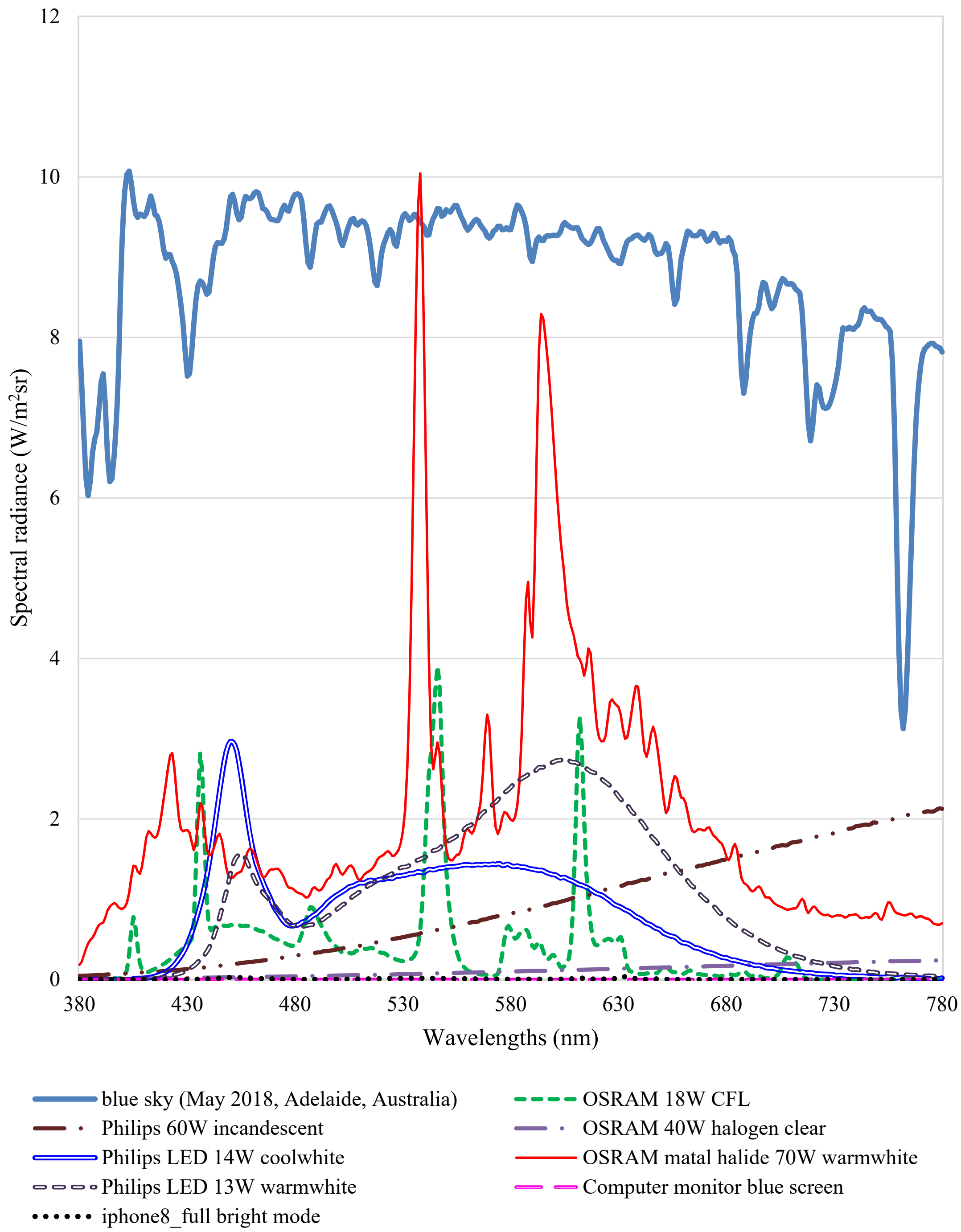


Figure A1. 1 Spectral radiances of typical light sources measured by Specbos 1211UV
(measurement distance between typical light sources and a spectroradiometer: 100 cm, excepting blue sky (∞), computer monitor (70 cm) and iphone8 (20 cm))

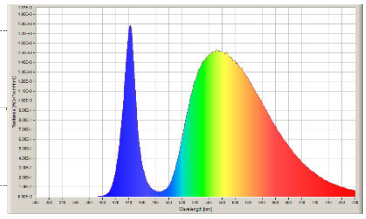
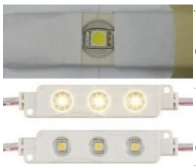
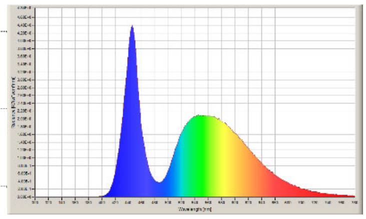
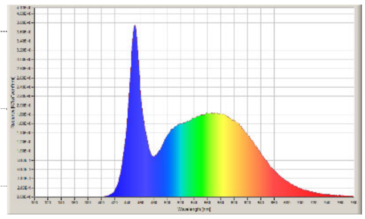
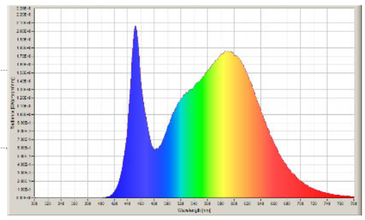
A1.2 Use of ICNIRP criteria for selected sources at a 20 cm viewing distance

In order to understand blue-light photochemical retinal damage risk, the acceptance averaging angle, 0.1 radian, provided by ICNIRP guidelines was considered. For this, four blue light sources (0.24W cool- and warm white single LED unit: Jaycar Electronics Company, 14W cool daylight LED globe: Philips Company, and 5W desk lamp with 3 colour temperatures: Sirius Company) were measured.

Of those light sources, single 0.24W spot sources were isolated from cool white and warm white LED strips. In order to understand various radiance values of a lamp with multiple light sources, a 5W desk lamp, with two different colour LED units (0.29W, 12 cool-white LED units and 5 warm-white LED units) in three rows, were measured by colour temperatures (3000K, 4500K and 6000K).

Table A1.2 shows the emission characteristics and graphs of the spectral radiance of each light source measured at 20 cm distances (hazard distance provided by AS/NZS IEC 62471:2011).

Table A1. 2 Emission characteristics of artificial blue light sources – centre targeted

Light sources	Picture	Specbos values		Spectral output (centre targeted)
0.24W cool-white single LED unit		Luminance (cd/m^2)	125500	
		CCT (k)	6670	
		Spectral radiance (W/m^{2}sr)	410	
		Blue-weighted radiance (W/m^{2}sr)	124	
0.24W warm-white single LED unit		Luminance (cd/m^2)	83430	
		CCT (k)	3478	
		Spectral radiance (W/m^{2}sr)	261	
		Blue-weighted radiance (W/m^{2}sr)	44.05	
14W Philips cool daylight LED globe		Luminance (cd/m^2)	121200	
		CCT (k)	6039	
		Spectral radiance (W/m^{2}sr)	389	
		Blue-weighted radiance (W/m^{2}sr)	109	
Desk lamp (6000K mode)		Luminance (cd/m^2)	104300	
		CCT (k)	4179	
		Spectral radiance (W/m^{2}sr)	316	
		Blue-weighted radiance (W/m^{2}sr)	82	
		Blue-weighted radiance (W/m^{2}sr)	111	

A1.3 Assessment of blue light exposure within acceptance viewing angle (6 degrees)

Measurements were conducted at nine points across a 0.1 radian (the same unit with 6 degrees) acceptance angle vertically and horizontally, as per ICNIRP guidance (see Figure A1.2).

The 5W desk lamp with 17 small LED units showed different targeting approaches with the singles sources (Figure A1.3). Depending on the three different colour temperatures of a desk lamp, targeting of the LED units in the lamp was different with other single sources.

Experiments in quadruplicate were conducted and the data were calculated by averaging values of each targets.

The levels of the L_B depended on the acceptance viewing angles by distances.

0.24W single cool white LED, 14W cool daylight LED globe exceeded the limit, 100 W/m^2sr, however, the average values within 6 degrees were only 44.82 W/m^2sr for 0.24W cool-white LED. Depending on power, sizes, colour temperatures of light sources and measurement distances, the levels of the L_Bs varied (Table A1.3).

Interestingly, the levels of L_Bs of a 5W desk lamp showed different patterns with other single sources (see Figure A1.3). Five warm-white LED units are located in the middle of the desk lamp and the average L_B of 33.73 W/m^2sr was higher than the cool white one (17.49 W/m^2sr) (Table A1.3).

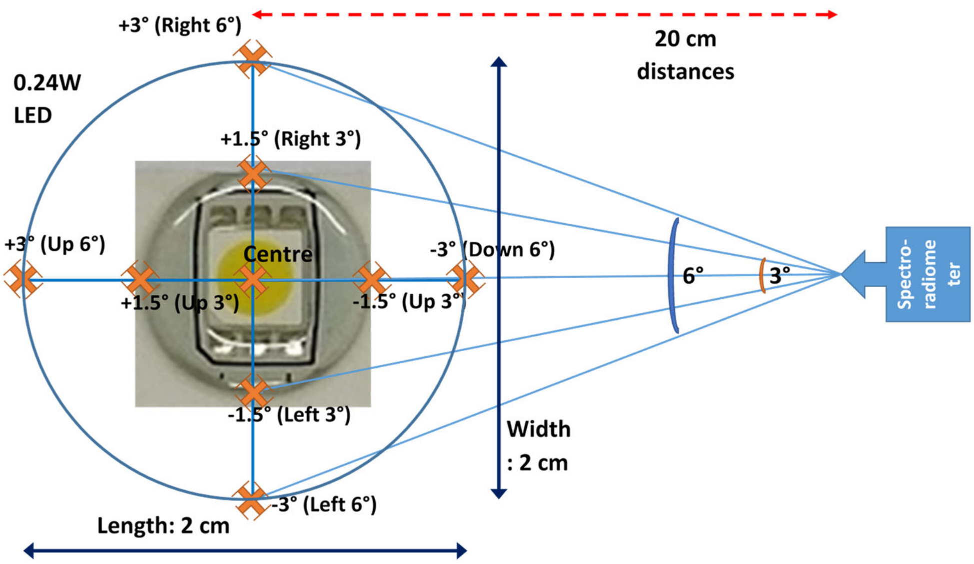


Figure A1. 2 An example of measurement of radiances from an approximate point source across a 0.1 radian (6 degrees: 2 cm in diameter) acceptance angle at 20 cm distances

Figure A1. 3 The range of acceptance averaging angle (6 degrees: 2 cm in diameter, red circle) of a desk lamp (from the left to right: 3000, 4500 and 6000K) at 20 cm distances.

Table A1. 3 The effective spectral radiance of various light sources within 6 degrees at 20 cm distances. One dimension only.

Light sources	Spectral radiance (W/m^2sr) by targets (degree)					
	-3	-1.5	centre	+1.5	+3	Avg
0.24W single LED unit cool-white	0.37	57.11	**116.29***	50.04	0.27	**44.82**
0.24W single LED unit warm-white	0.11	7.70	**41.28**	5.44	0.05	**10.92**
14W Philips LED globe	100.27	104.88	**106.91***	106.70	105.71	**104.90***
3W Desk lamp (3000K)	22.33	16.63	**72.56**	29.99	27.16	**33.73**
3W Desk lamp (4500K)	15.34	19.78	**11.49**	18.82	22.03	**17.49**
3W Desk lamp (6000K)	36.02	35.23	**81.69**	43.67	47.19	**48.76**

* L_{BS} exceeded the maximum acceptable limit (100 W/m^2sr) within 10,000 sec.

Note that coverage of the viewing angles increases as the measurement distances increases and the levels of L_{BS} within 6 degrees showed large difference. For example, the L_{BS} of a 14W cool daylight LED globe at 20 cm showed similar levels of L_{BS} within 6 degrees (from 100 to 10^6 W/m^2sr), while the values of the L_{BS} at 200 cm distances showed large gaps between the centre (68 W/m^2sr) and 6 degrees (0.37 W/m^2sr).

More detailed experimental data regarding point sources with the lowest power and a desk lamp with 17 small LED units are described as follow.

Spot sources assessment at 20 cm distances

To identify the effective blue-weighted radiances (L_B) between 0.1 radian (around 6 degrees), point sources (0.24w LEDs cool-white and warm-white) were used in the experiment and were measured at 20 cm within 0.1 radian. The most intense L_B in 0.1 radian angles was the centre target (116 W/m^{2}sr and 41 W/m^{2}sr) (Table A1.3) and it exceeds the radiance limitation ($L^{EL}{}_B$ = 100 W/m^{2}sr, if t > 10,000s). Therefore, the permissible exposure duration of the 0.24w cool-white LED targeted in the centre is less than 10,000 sec and that is to say the maximum exposure duration t_{max}[s] of the LED is 8,620 sec (calculated from ACGIH formula for maximum acceptable exposure duration).

For eye movements, nine spots (centre, right, left, up, and down) within 6 degrees were targeted (Figure A1.2), and the graph in Figure A1.4 was made from the average of each 3 degrees for viewing. A total of four experiments was conducted and the data were calculated by averaging values of each targets.

The averages of L_B for a cool-white and a warm-white were 44.82 W/m^{2}sr and 10.92 W/m^{2}sr respectively (Table A1.3) and these show the amount of average blue light exposure of the point sources within 6 degrees during eye movements. The graph in Figure A1.4 also shows the colour difference between cool-white and warm-white. The maximum and average radiances of the warm white LED are within the limits and the centre target L_B of a cool-white is three times higher than the warm-white's.

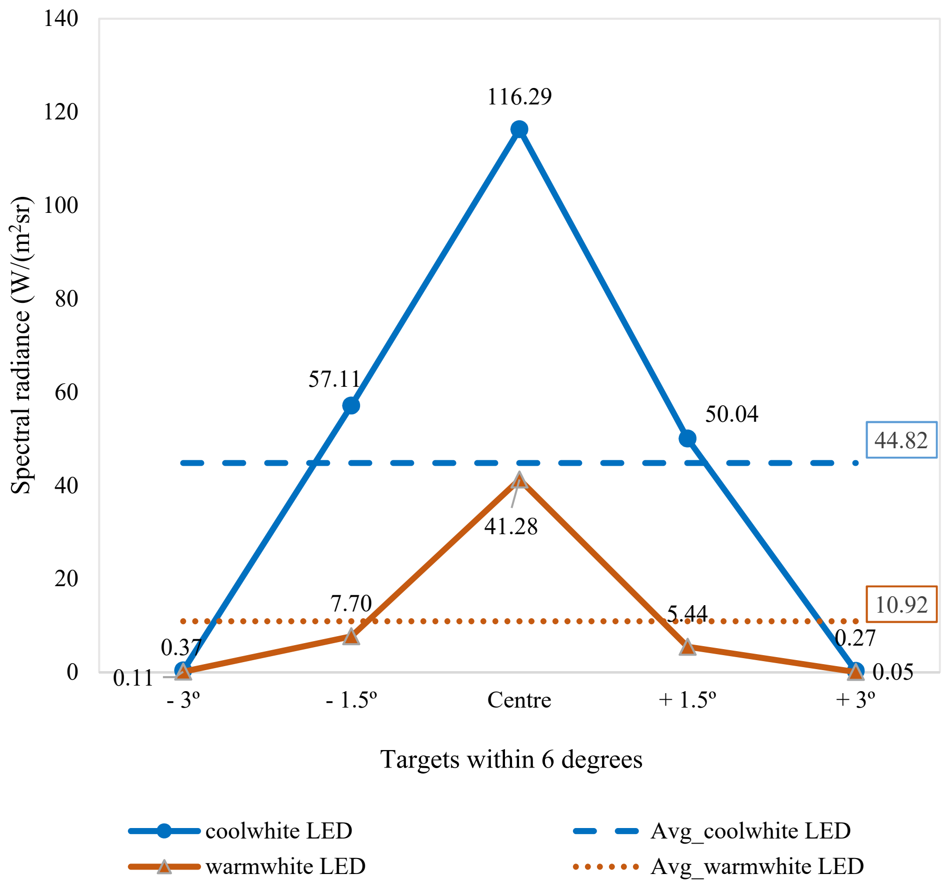


Figure A1. 4 The effective spectral radiance of two 0.24W LEDs at 20 cm distance. One dimension only.

A desk lamp assessment at 20 cm distances

Unlike a point source above, a desk lamp has 17 small LED units arranged horizontally and the levels of the L_Bs of the desk lamp within 6 degree depended on viewing points and colour temperatures (Figure A1.3).

The highest radiance was the centre of the 6000K desk lamp (L_B = 84 W/m^{2}sr). The averages of the L_B for 3000K, 4500K and 6000K of a desk lamp were 33.73, 17.49 and 48.76 W/m^{2}sr respectively (Table A1.3) and these show the amount of average blue light exposure of the desk lamp within 6 degrees during eye movements at 20 cm distances. The graph in Figure A1.5 also showed the colour difference between cool-white and warm-white and mixed colours. Interestingly, the centre and the average values of the L_B of the 4500K were lower than the 3000K's because the warm-white LED unit is located in the centre of the desk lamp and there is no light source in the centre of 4500K of the desk lamp when the target of the spectroradiometer was in the centre of the lamp. The maximum and average radiances of the points of the lamp did not exceed the limit of L_B, 100 W/m^{2}sr (Figure A1.5).

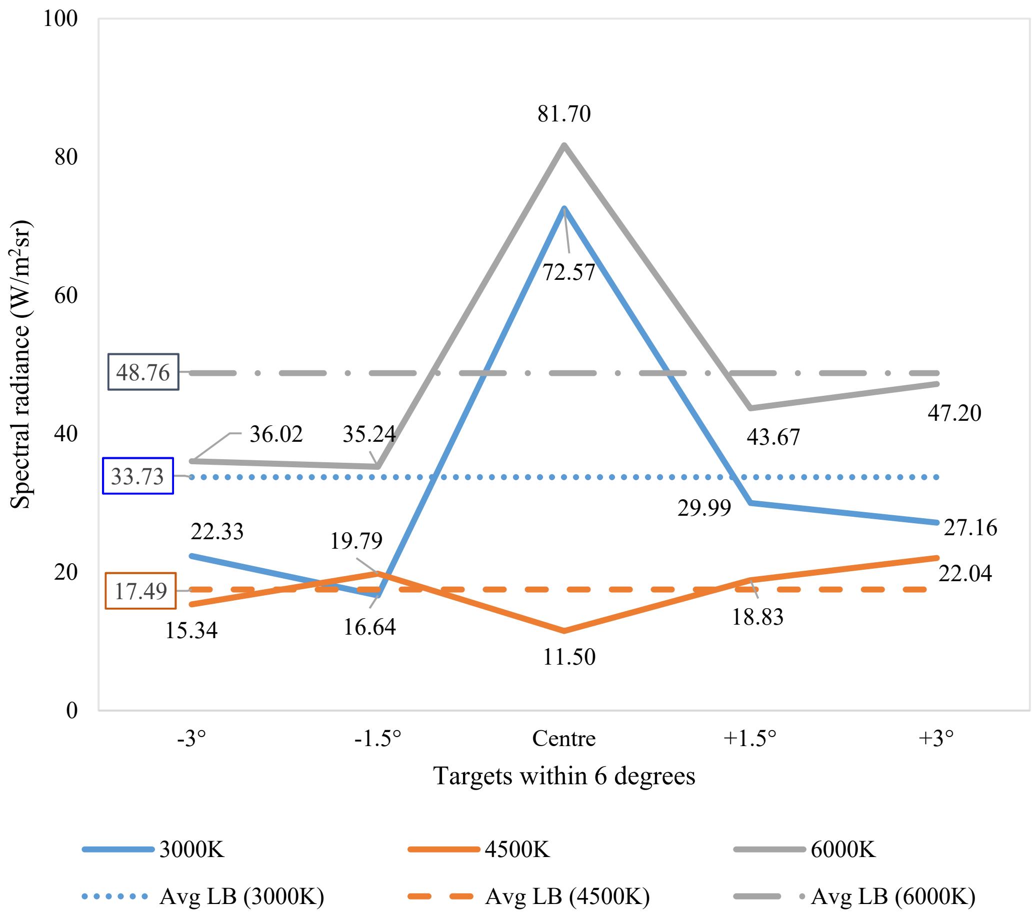


Figure A1. 5 The effective spectral radiance of a desk lamp by colour temperatures at 20 cm distance. One dimension only.

A2. Usefulness of a luminance meter with a blue filter for identifying blue light sources

Using a spectroradiometer, the physical characteristics (e.g. photometric and radiometric data) of light sources can be identified and assessed. Unlike hand-held photometers such as a luminance and illuminance meter, which can be commonly used to measure light sources, the spectroradiometer, which can provide all characteristic information of light sources including blue-weighted radiance, requires a set-up and is rarely used in workplaces. In addition, it is expensive compared to the other equipment for measuring light sources. According to Okuno's study (1988), a luminance meter could emulate blue-weighted spectral radiance if appropriate blue filtering is used and correction factors determined with a spectroradiometer.

Based on this concept, Appendix A2 describes the assessment of light sources using a luminance meter with a blue filter.

A2.1 Methods

Instrumentation

A luminance meter (Minolta camera CO., LTD. Japan, S/N: 401626, calibrated by the QUT Photometric Laboratory) with a blue filter (HOYA company, glass type: B440, 50×50 mm) was used to measure the blue-weighted luminance (Figure A2.1 and Figure A2.2). The luminance and spectral radiance were measured using the spectroradiometer (Specbos 1211UV).

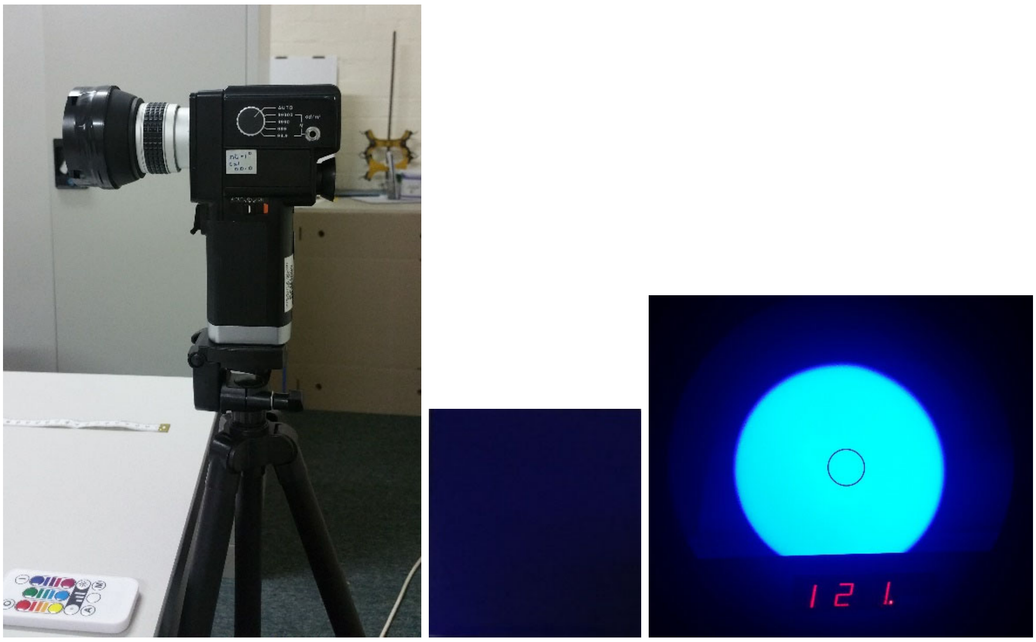


Figure A2. 1 Experiment equipment
(left to right: a luminance meter (Minolta luminance meter) with a blue filter, a blue filter-used (HOYA B440) and an example of the value of blue-weighted luminance on the luminance meter installed the blue filter)

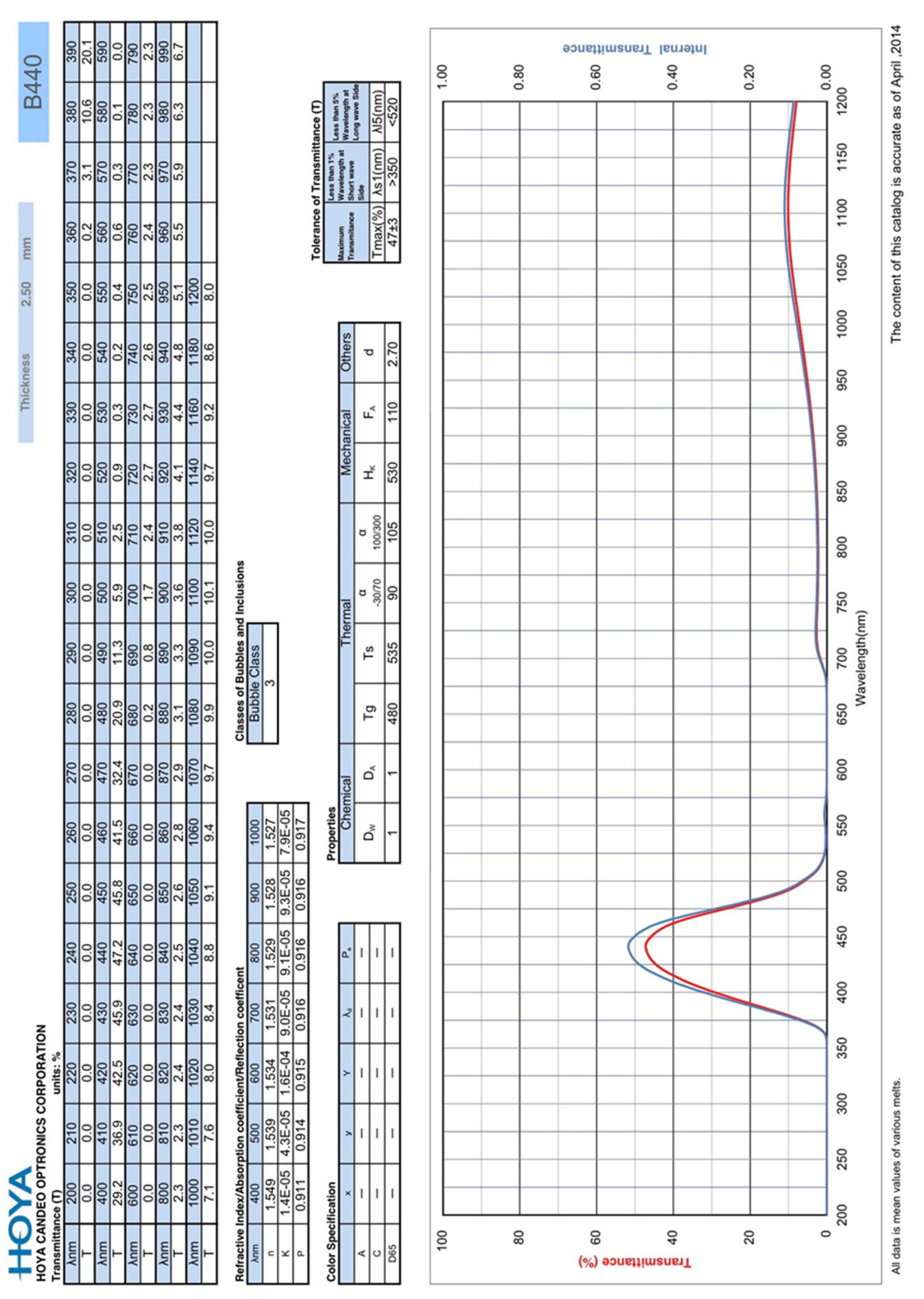


Figure A2. 2 Blue filter (Hoya Company, B-440) data
(retrieved 3 Sep 2019 from http://www.hoyaoptics.com/eo_pdf/B440.pdf)

Assessment of light sources

In order to see the differences between luminance (Lv) and blue-weighted luminance (Blue Lv) of different coloured light sources, a colour-changing RGB LED globe (2.8W, Mortbay company) with 16 different colours based on red, green and blue and 5 steps of brightness was used by the remote (Figure A2.3). Table A2.1 shows actual colours of the RGB LED globe and all measurements were set up the brightest mode (step 5 out of all 5 steps).

In addition, typical artificial sources emitting blue wavelengths (Mirabella LED 20W 6500K, Brilliant Halogen 42W 2700K, Philips LED 14W 6500K, Philips LED 13W 3000K, Coles 10W LED cool-white) were also used to measure the Blue Lv (Table A2.2).

Figure A2. 3 A colour-changing LED globe (Mortbay RGB) (left) and the remote for changing colours (right)

Table A2. 1 Actual colours displayed on the remote of a colour-changing LED globe (brightness: step 5_the brightest mode)

Colour / Step	Red	Green	Blue
1			
2			
3			
4			
5			
White			

Table A2. 2 Emission characteristics of various artificial light sources measured by the spectroradiometer

Light source (measurement distance)	**Luminance (cd/m^2sr)**	**Radiance (300-780 nm) (W/m^2sr)**	**CCT (K)**	**Blue-weighted radiance L_B (W/m^2sr)**
Mortbay RGB LED 2.8W dimmable White (20 cm)	2,469	10	5,070	1.76
Mirabella LED 20W Daylight 6500K (20 cm)	8,4380	297	8,642	85.32
Brilliant Halogen 42W 2700K clear bayonet (20 cm)	323,300	2,109	2,809	93.36
Philips LED 14W 6500K edison Cool Daylight (20 cm)	108,000	347	6,046	87.23
Philips LED 13W 3000K edison Warmwhite (50 cm)	157,000	479	3,053	49.49
Coles 10W LED cool white bayonet (50 cm)	36,190	112	4,067	17.72

The dark room lab experiments with the light sources-used were conducted as shown in Figure A2.4 with targeted measurements at the centre in front of the lamps. The lamps were measured in triplicate at 20 cm and 50 cm distances and L_{VS} and Blue L_{VS} using the luminance meter and the spectroradiometer. The average values are reported.

Figure A2. 4 Examples of measurement setup
(the measurement of blue-weighted luminance (Blue Lv) using the luminance meter with a blue filter (top) and spectral radiance using the spectroradiometer (bottom))

A2.2 Results

RGB light source assessment

This experiment sought to identify blue-weighted luminance using a colour-changing RGB LED globe. Table A2.3 shows the outcomes of the RGB LED globe using the luminance meter with a blue filter and the spectroradiometer.

As expected, L_Bs of colour blue settings (Blue 1 to Blue 5: 7.62 to 5.43 W/m^{2}sr) were higher than colour yellow's and green's L_Bs (Red 1 to Breen 5: 0 to 3.93 W/m^{2}sr) although higher luminances (L_Vs) were found in yellow and green colours than colour blue settings. The range of Blue L_Vs in Blue 1 to 5 was from 116 to 157 cd/m^2 compared to the range of Blue L_Vs in Red 1 to 5, from 0.1 to 12.6 cd/m^2. In the proportion of emission of blue light between L_B and blue L_V, the range of colour blue (Blue 1 to Blue 5) showed the highest values, 4.59 % to 4.83 %, and the range of colour red (Red 1 to Red 5) showed the lowest levels of the proportion from 0 % to 1.08 % (Table A2.3).

The initial experimental results are in Table A2.3.

Table A2. 3 Comparison on the values of Blue L_V from the luminance meter with a blue filter and L_B from the spectroradiometer

Colours	Measured by **Specbos 1211UV**			Measured by **Minolta with a blue filter**	**Proportion of emission of blue light (%)**[#]
	Colour temperature (k)	**Blue weighted radiance (L_B, W/m^{2}sr)**	**Luminance (L_V, cd/m^2)**	**Blue-weighted luminance (Blue L_V, cd/m^2)***	
White	5070	1.76	**2469**	47.8	3.68
Blue 1	-	**7.62**	977	**157.5**	**4.83**
Blue 2	-	5.55	902	120.8	**4.59**
Blue 3	-	5.55	1064	118.6	**4.67**
Blue 4	-	5.49	1314	118.1	**4.64**
Blue 5 (Violet)	-	5.43	1445	116.3	**4.66**
Green 5 (Sky blue)	-	3.93	1760	93.7	4.19
Green 4	-	3.16	**2055**	81.1	3.89
Green 3	-	1.83	1868	53.1	3.44
Green 2	-	1.02	1760	35.8	2.84
Green 1	-	0.24	**2088**	23.3	1.03
Red 5 (Yellow)	2265	0.13	**2113**	12.6	1.03
Red 4 (Yellow-orange)	1884	0.11	1901	10.1	1.08
Red 3 (Orange)	1331	0.06	1526	5.6	1.07
Red 2	-	0.03	1288	2.8	1.07
Red 1	-	0.00	1298	0.1	0

* Calibration factor of the luminance meter: 1.25
[#] Blue-weighted radiance (L_B) / Blue-weighted luminance (Blue L_V) × 100

Assessment of other light sources

After the RGB LED assessment, additional experiments were conducted to assess the blue-weighted luminance of six typical artificial light sources generally used in workplaces. This experiment showed some interesting results.

The L_B of 14W cool daylight LED showed the highest value, 93.6 W/m^{2}sr. The 42W halogen lamp showed the highest luminance value, 320770 cd/m^2. In the proportion of emission of blue light between L_Bs from the spectroradiometer and blue L_Vs from the luminance meter with a blue filter, LEDs with white colours (the range of colour temperature: 4067 to 8657 K, see in Table A2.4) showed higher percentages (5.16 to 7.73 %) than a warm white LED's percentage (4.54 %). In particular, 42W Halogen globe with the highest L_V showed a very high level of L_B, 92.7 W/m^{2}sr and had the highest rate of emission of blue light at 11.21 %.

Table A2. 4 Comparison on the values of blue-weighted luminance and luminance of various light sources

Light sources (measurement distance: cm)	Measured by Specbos 1211UV			Measured by Minolta with a blue filter	Proportion of emission of blue light (%)#
	Colour temperature (K)	Blue weighted radiance (L_B, W/m^2sr)	Luminance (cd/m^2)	Blue-weighted luminance (Blue L_V, cd/m^2)*	
Mirabella LED 20W 240V edison Daylight (20 cm)	8657	79.9	79052	1085	7.36
Philips LED 14W 6500K edison Cool Daylight (20 cm)	5966	93.6	117745	1210	7.73
Brilliant Halogen 42W 2700K clear bayonet (20 cm)	2806	92.7	320770	827	11.21
Philips LED 14W 6500K edison Cool Daylight (50 cm)	6067	84.4	104130	1221	6.90
Philips LED 13W 3000K edison Warmwhite (50 cm)	3055	49.4	155370	1086	4.54
Coles 10W LED cool white bayonet (50 cm)	4067	17.6	35830	341	5.16

* Calibration factor of the luminance meter: 1.25

Blue-weighted radiance (L_B) / Blue-weighted luminance (Blue L_V) × 100

Appendix B.

Use of mobile phones for workplace lighting environment assessments

The global mobile market has seen tremendous growth in recent years and it is estimated that 67.2 % of the overall Australian population will be using a smartphone by 2018 (Statista, 2017). With the popularity of mobile devices, various easy-to-use applications have been created and are being used currently. Initial applications using mobile sensors were available with separate attachable accessories on mobiles but with quickly evolving mobile technology, software/sensors have been developed to eliminate the need for such attachments. New mobile devices have various functions including; movement direction sensors (e.g. accelerometer, gyroscope and magnetometer), sound and light sensors (Liu, 2013). Through these sophisticated technologies, one can perform many functions with just one mobile device. Many mobile apps using multifunctional sensors can be used in the occupational health field, for example, health monitoring or health surveillance using GPS apps or noise monitoring using noise meter apps (Hovila et al., 2005, Triantafyllidis et al., 2017).

Appendix B described use of smartphone applications for initial lighting surveys.

The sections of Appendix B are as follow.

B1. Google Street View (3D) for preliminary light surveys

B2. Comparison of light meter apps with professional lux meter in an office setting

B3. Can a mobile phone be used for blue light assessment?: preliminary experiments with a blue filter on mobile phone light sensor.

B1. Google Street View (3D) for preliminary light survey

"Google Street View (GSV)" is an application running in Google Maps and provides 3-Dimensional (3D) images in the Internet. With various sophisticated sensors associated with IT devices, such as geographic and camera sensors, this app enables us to show directions and finds places we want to go in the world, virtually.

The GSV app has been used in geographic information, education, physical activity, health monitoring/surveillance or quality of social/daily life (Brookfield and Tilley, 2016, Parra et al., 2016).

However, it appears that the GSV app has not been used to assess the lighting environment in the workplace.

Human eyes are very directional and it is not easy to evaluate lighting environments from various different types of light sources, especially in a large room. The potential health effects (e.g. circadian rhythm, asthenopia, macular degeneration or psychological issues) from the exposure to bright light sources, especially in workplaces, are emerging as health-related issues. For these reasons, lighting surveys are generally useful and there are various survey techniques, e.g. quantitative surveys and direct observational surveys (Pisaniello et al. 2017). As the initial observation for light surveys, 2-dimensional (2D) floor plans or still photographs are generally used in lighting environments. 3D approaches using a 3D camera can be more appropriate for the initial lighting observations. However, the 3D cameras are generally quite expensive, ranged from $1,000 to over $5,000, and not common devices in occupational settings. However, GSV is a free app and most smartphone users can use anywhere.

B1.1 Methods

3D photos were taken by a smartphone camera (Galaxy Note 4) using GSV app in the video recording studio in the University of Adelaide.

The 3D photos were uploaded in the researcher's Google account (Figure B1.1).

Figure B1 1 An example of a 3D photo of the video recording studio (Google webpage: https://photos.google.com/share/AF1QipOmu2RyfyvliEdI6ps3P0mzEjUC9GMmoPZUZcHtxtADqkgbW34HA6_K5-R-p3NcRw/photo/AF1QipPgg055-nYBGHScUh9-MFJ71OaA9XgF1ZkOP3-A?key=b0t6YXRYM2oyYlJsLTA1MWFpMFBXTUhWWHRwQ1pR)

B1.2 Use of Google street view as a preliminary investigation for lighting surveys

Three-dimensional photos using a mobile application can help to identify spatiotemporal data of working spaces that do not appear on a floor plan or typical two-dimensional pictures. Google street view (GSV) is one of the applications which can take 3D or panorama photos and provide the images in Google Maps and Google Earth. It can be used in many ways, from architecture to even augmented reality games, these days, and occupational hygienists can evaluate/estimate field work lighting environments faster/more convenient/simply.

The 3D photos in the GSV app can be shared to many people at the same time and can obtain objective preliminary observational data in several respects. This app can help to improve the quality of lighting survey and the data (3D photos) can become the initial information for future technology for lighting surveys in the workplace. However, distortion of 3D images can appear and inaccurate spatial information may be provided. The upgrade of these types of applications for the actual field work investigation is still required. The GSV can sometimes lead to inadvertent disclosure of personal information.

Table B1.1 is a comparison table between the GSV app, a commercial 3D camera, a general 2D photo and a 2D floor plan for the lighting survey.

Table B1. 1 Comparisons between a floorplan, mobile phone camera and 3D camera

	Pros	Cons
Google Street View	• All smartphone users can use • Portable • Record accurate times and locations • Free or low cost	• The quality of a photo depends on mobile phones • Spatial distortion • Longer shooting time than 2D cameras (up to 2 min) • Security risks
3D camera	• Higher quality 3D photos than mobile phone cameras • Increasing the market continuously	• High price ($1,000 – over $5,000) • Spatial distortion • Longer shooting time than 2D cameras
2D photo	• Generally higher quality photos than 3D photos • Short shooting time than 3D cameras	• Show only one side, No provide whole space-information with one 2D picture • Hard to find distances with a 2D picture (It is not well represented perspective and visual depth perception of spaces)
Floor plan	• Easy to understand whole sizes and distances of a space at a glance	• Hard to read spatial structure and characteristics of a space • Some floor plans are too technical for a non-specialist

B2. Comparison of light meter apps with professional lux meter in an office setting

Light meter applications work through a light sensor which is located inside a smartphone for taking photos and are able to show light intensity levels. These apps can sense light and measure illuminance. They may become very useful portable devices that can be used instead of a lux meter in occupational settings.

Research purpose

This study is focussed on the applicability of mobile phone light meter apps for measuring illuminance values in occupational settings, as an alternative for using lux/illuminance meters.

Using existing literature and results of illuminance and BLHF illuminance from tests in a mock-up workstation, the following questions were explored

[1] Are the mobile phone apps' light sensor suitable for lighting survey?

[2] What is the performance of light meter apps relative to a professional lux meter?

[3] Are there types of mobile phone apps that are more reliable than other?

B2.1 Are the mobile phone apps' light sensor suitable for lighting survey?

Goldschmidt and Pittner (2016) provided the initial data and ideas about the use of mobile apps for illuminance measurement. They measured the illuminance values from seven mobile apps in seven different types of mobile devices on a horizontal surface and set up three reference illuminances (100 lx, 500 lx and 1,000 lx) using an illuminance meter (PRC Krochmann) under three different light sources. The range of deviations of the apps according to the reference illuminances in the predetermined lighting conditions were from 3 % (the lowest) up to 113 % (the highest) and the apps of Android and Windows phones showed the higher illuminance values than the reference illuminance and the other apps with iOS operating system indicated the lower illuminances than the references. In addition, four iPhone 5 mobiles showed different outcomes (all lower) under 3 different reference values. With one iPhone loaded with 2 different apps, again different outcomes (all lower) from each app were obtained. (Goldschmidt and Pittner, 2016)

In a larger and more recent study than the paper above, Cerqueira et al. (2018), examined the accuracy of 14 light meter apps using 138 mobile phones with three different operating systems (Android, iOS and Windows). They set up three different coloured light sources in a black chamber and designated four reference illuminance values (300 lx, 500 lx, 750 lx and 1000 lx) for comparison. The higher the illuminances from the reference light meter, the greater was the spread of data from the apps. Depending on colour temperature (2700 K, 4000 K and 6500 K), the brighter the light sources (i.e. the higher the colour temperature), the smaller the differences in values of the illuminances measured. They mentioned that the applications with calibration functions showed significantly lower mean deviations, however, the range of deviations' ratios was still from 31.1 to 50.8 %. (Cerqueira et al., 2018)

From both studies, it would be premature to think that smartphone light meter apps are capable of replacing existing lux meters for professional measurement.

Johnson et al. (2015) showed variable outcomes from their new light intensity calculation app, Access Light, and reported this app could measure lux values comparable with a professional light meter. Parra et al. (2016) stated that the error rates between Access light and a professional light meter were only 5 %).

B2.2 Assessment methods

Workstation set-up

All tests were conducted in the mock-up office which was set up in the laboratory which had no extraneous light, only light sources being the fluorescent ceiling lamps (Figure B2.1(a)) The workstation was set up with typical equipment (including IT devices) from general office supplies. The height of the desk was 0.7 m and the height of downlights to be tested was set up to be perpendicular to the desk and 1.9 m from the desk. One spot in the centre of the workstation was designated to measure the illuminance and all tests using mobile apps and an illuminance meter were conducted in this fixed spot (Figure B2.1).

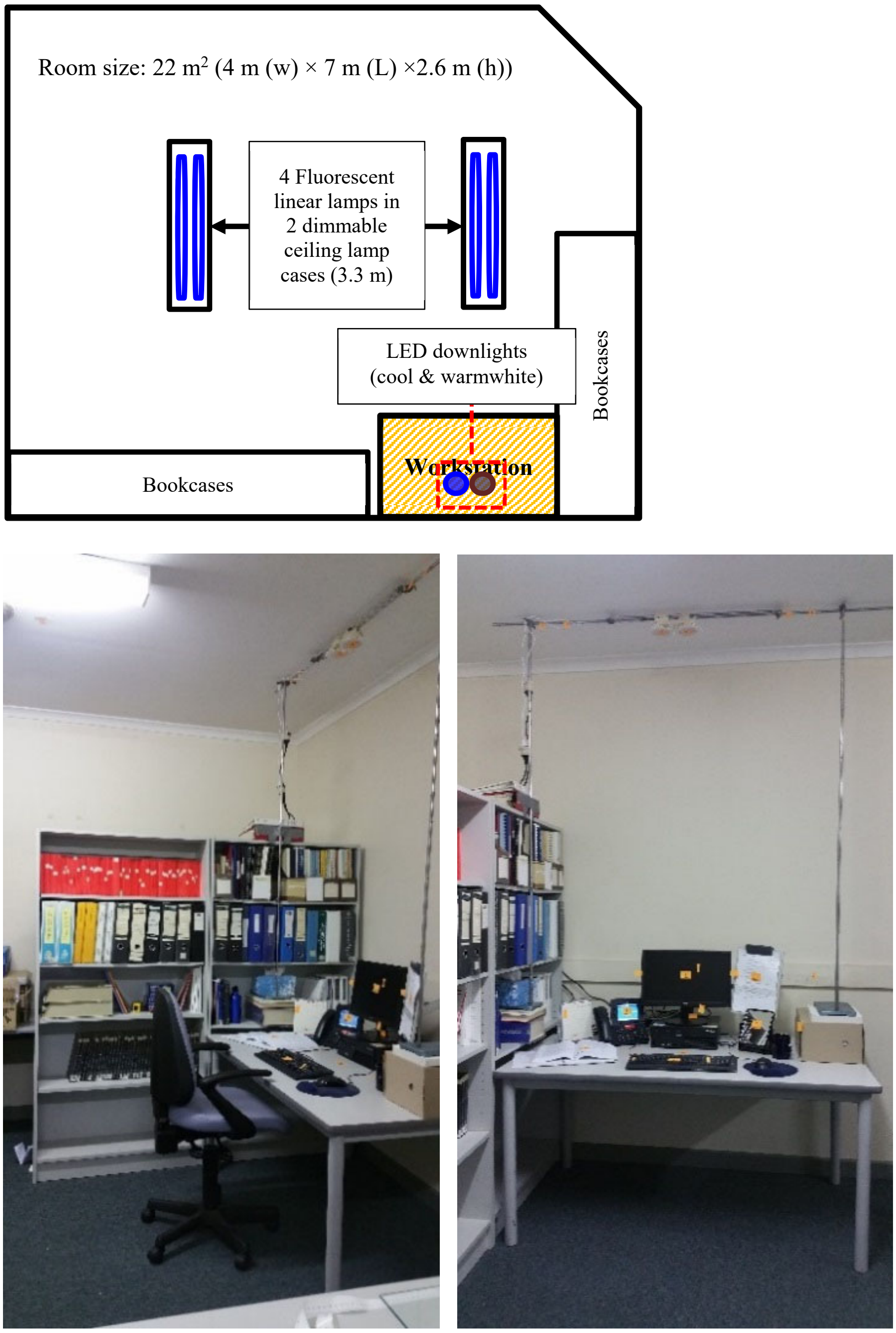


Figure B2. 1 Simulated workstation in the office
(top to bottom (a) floor plan (b) & (c) pictures of the simulated workstation)

Characteristics of the Light sources

One DETA 12W cool-white (Model: DET492) and one warm-white (Model: DET490) LED was set up in the ceiling above the workstation. Two twin OSRAM 36W linear fluorescent tubes (Model: L36W/840) in two twin prismatic diffusers were used as luminaires for testing of background lighting (Table B2.1). All measurements were taken in the fixed spot location on the desk and all brand-new lamps excepting ceiling mounted fluorescent linear lamps, were used in the all tests.

Table B2. 1 Emission characteristics of light sources

Measuring equipment	Measurement	DETA 12W Cool-white LED downlight /DET492	DETA 12W warm-white LED downlight /DET490	OSRAM 36W fluorescent linear tube /L36W/840
Spectro-radiometer	Luminance [cd/m^2]	75257	66451	6452
	CCT [K]	5672	3023	4062
	L_B [W/m^2·sr]	56.47	22.36	3.28

Two LED globes (Philips/14W cool- and 12W warm-white), a CFL twist blub (OSRAM/18W daylight/model No.: 865) and two halogen globes (Mirabella/40W/pearl dimmable and OSRAM/28W natural light/clear) were used to measure and compare the illuminance values in various lighting conditions.

Applications and Devices

Six smartphone devices and two tablet PCs were used for testing the illuminance. They had two different types of operating systems, Android and iOS, which are the most commonly used around the world (Table B2.2). The screen mode of all devices was set up at maximum brightness. Two free applications for two different operating systems were downloaded from each of the websites. An illuminance meter (Digital Lux Tester, National Company, BN-2000LTE), was used as the reference device to compare the values of the illuminance from mobile apps (Figure B2.2).

A Specbos 1211 UV (JETI Germany, S/N: 2010143) spectroradiometer, with LiMeS software (Version 4.1.0m), was used to determine the characteristics (e.g. luminance, actual colour temperature or spectral radiance) of the light sources in the workstation.

Table B2. 2 Types of hardware and software depending on mobile devices

Model	Operating system	Used applications/provider
Samsung Galaxy Note 4 Samsung Galaxy Note 3 Samsung Galaxy S5 Motorola Razr	Android	Light Meter/Trajkovski Labs
iPhone 4s iPhone 7 iPad mini iPad pro	iOS	LUX Light Meter/Nipakul Buttua

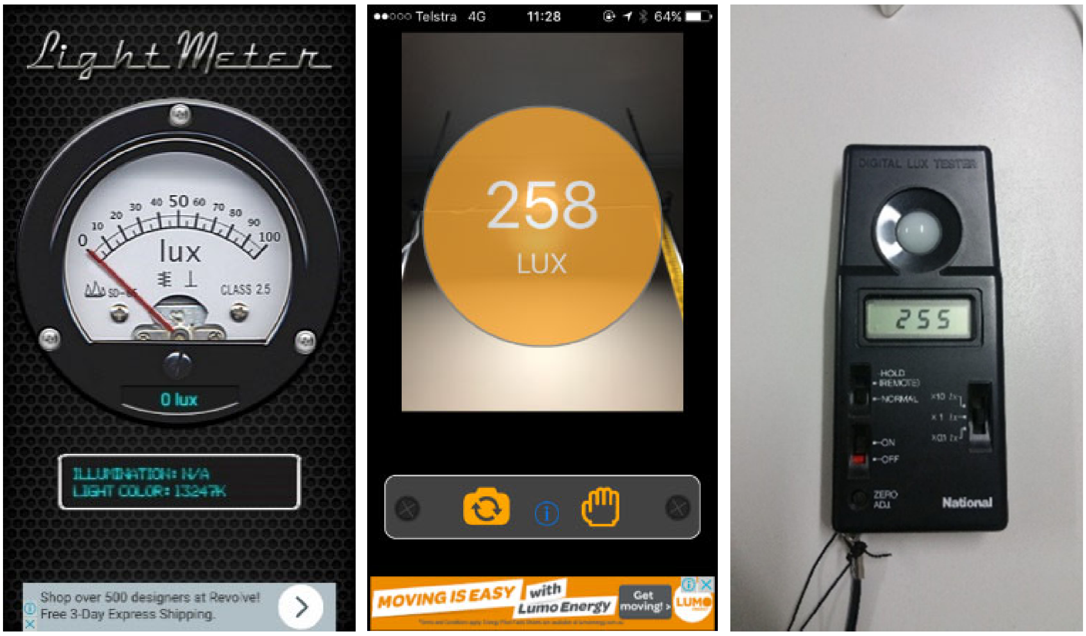


Figure B2. 2 Mobile phone apps and illuminance meter.
(left to right (a) light meter application for Android, (b) light meter application for iOS and (c) National lux tester)

Lighting standards for the illuminance of indoor workplaces

Standards referred to for conducting all lighting tests were as follows.

- AS/NZS 1680 – Interior and workplace lighting (Inform the measurement of the illuminance)
- CIE 117: 1995 - Discomfort glare in interior lighting (Provide definitions and measurements of glare)
- AS/NZS IEC 62471:2011 – Photobiological safety of lamps and lamp systems (Provide types of artificial light sources)
- ISO/CIE 19476:2013 Characterization of the performance of illuminance meters and luminance meters

B2.3 What is the performance of light meter apps relative to a professional lux meter?

Mobile light meter apps and the reference lux meter

Mobile device apps and a lux meter were used to measure lux in six different lighting conditions to compare illuminance values. Firstly, vertical illuminances of mobile apps and lux tester were measured at the workstation using two downlight LEDs with different colour temperature (cool-white and warm-white). Reference illuminance values from the lux meter were 148 lx under a cool-white LED and 125 lx under a warm-white LED. The range of the illuminance values of mobile apps was from 91 lx to 296 lx and the comparative results varied significantly, whether under both cool- or warm-white LEDs. However, Mobile apps under the warm-white LED showed relatively lower values than the illuminance under the cool-white LED and these results indicate mobile apps can differentiate the illuminance of light depending on colour temperature.

Interestingly, iPhone and iPad installed iOS operating system have two light sensors in front and rear camera respectively and can detect illuminance with both sensors. However, a front light sensor produced significantly lower values than a rear sensor in a same mobile device.

To compare the difference between mobile light meter apps and the lux meter, the relative error was used. On average, the illuminance values under a cool-white LED were higher than under warm-white LED. Galaxy S5 and iPad pro rear camera showed the biggest disparity in the both light sources (Figure B2.3).

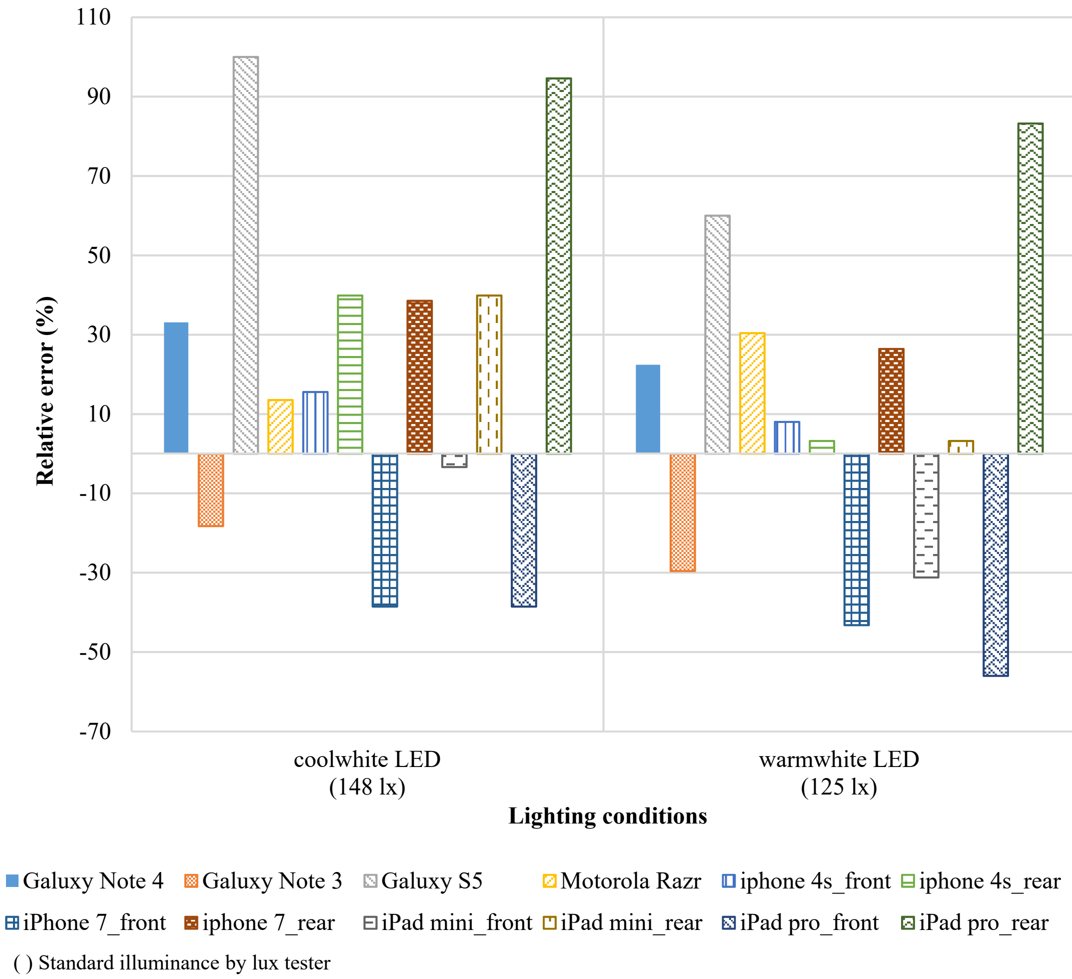


Figure B2. 3 Relative deviations from standard lux measurements for overhead sources

Two luminaires each with two linear fluorescent tubes, both with prismatic diffusers were fitted to the office ceiling, and were used to collect additional experimental data for assessing the illuminance values from multiple angles. The closer ceiling-mounted prismatic diffuser was located at around 2.2 m distance and an angle of 35° away from the fixed measuring spot and the further one was located at around 4.5m distance and an angle of 55° away from the spot. The additional lighting conditions were; cool-white LED and four fluorescents, warm-white LED and four fluorescents, four fluorescents only, and cool- and warm-white LEDs and four fluorescents. The reference values from a lux meter were 276, 260, 147 and 417 lx and the range of the illuminance values of mobile apps were 180 to 371 lx, 148 to 371 lx, 60 to 143 lx and 310 to 585 lx respectively from the left of the lighting conditions. iPhones' and iPads' front sensor showed lower, but variable illuminance values than the rear sensors. The illuminance values based on colour temperature in the multiple angles from the mixed lighting conditions did not show a big difference and the values from the lux meter also showed 276 lx in cool-white LED and four fluorescents and 260 lx in warm-white LED and four fluorescents.

Unlike the results under vertical down-lighting LEDs, illuminance values from multiple angles were more variable for all mobile devices. One of the notable points is that under the non-vertical lighting condition using only the fluorescent lamps, all mobile apps showed the significantly lower illuminance levels than the lux meter used. The range of the values was from 71 to 143 lx and the relative errors of all mobile apps were high at the other errors in the non-vertical lighting conditions (Figure B2.4).

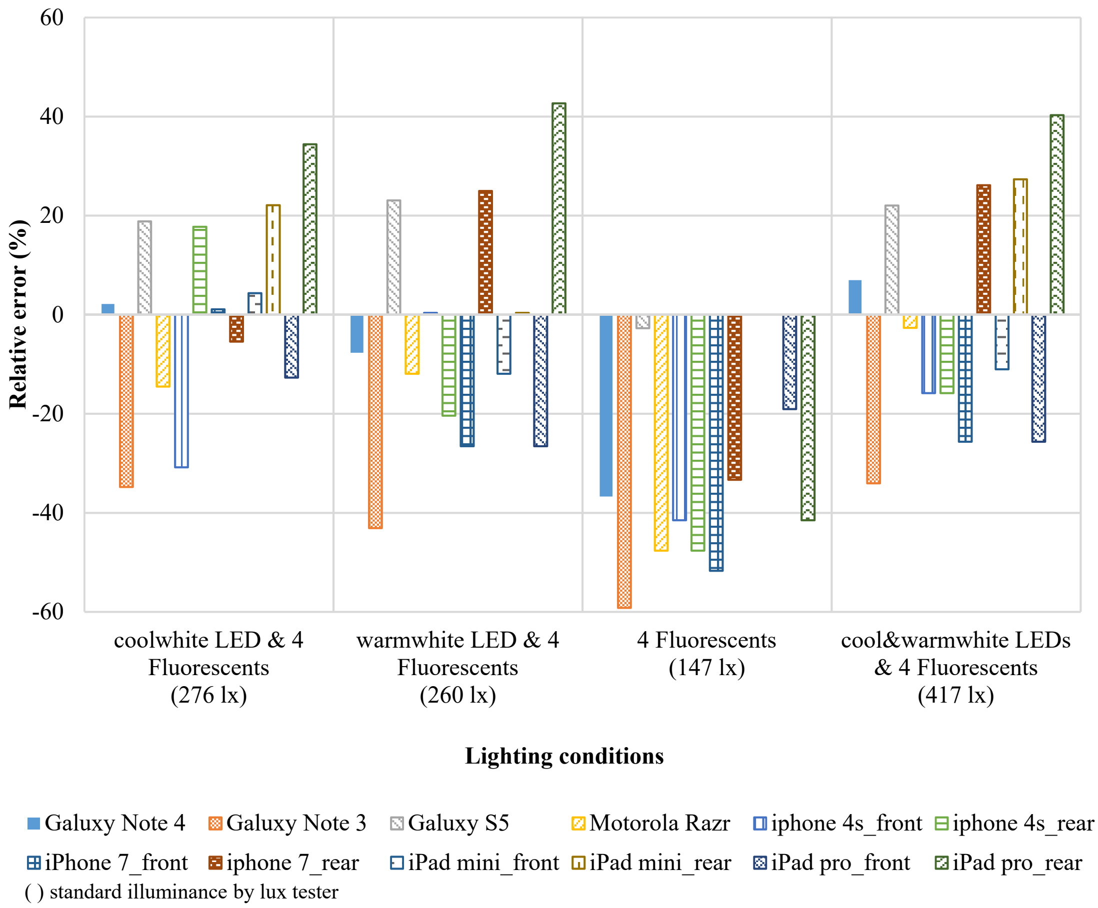


Figure B2. 4 Relative deviations from standard lux measurements for mixed sources

The most likely illuminance values of the lux tester were from Samsung Galaxy Note4. The illuminance values of Note4 were about 20 to 25 % higher than the lux meter in the vertical illuminance. However, the illuminance levels of Note4 showed more differences from the lux tester under non-vertical illuminances like other mobile devices and most levels in the non-vertical lighting conditions, excepting under the cool- & warm-white LEDs and four fluorescent lamps, were lower than the lux tester's levels.

Comparison between the standard and mobile apps

In order to compare illuminance levels of each mobile app under the same reference illuminance, 320 lx the workstation under vertical illuminance using a 12W cool-white LED downlight was set up. However, each app showed different outcomes for the reference, 320 lx, and even iPhones' and iPads' front and rear cameras in same smartphones showed significantly different outcomes (Figure B2.5).

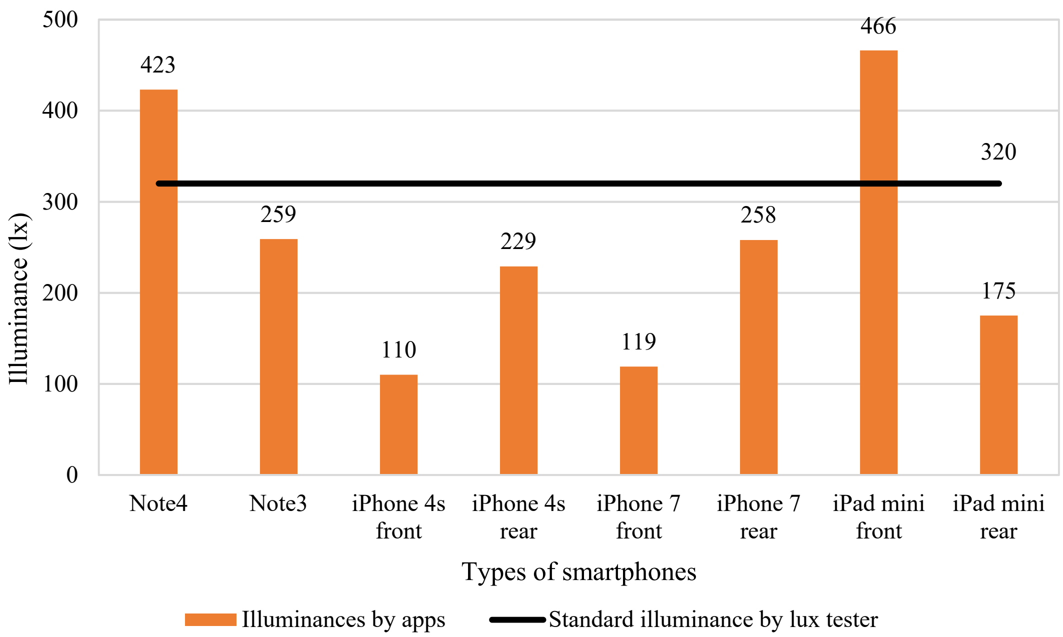


Figure B2. 5 Constant illuminances for one illuminance

Other light sources

As additional experiments, typical light sources with various powers, colour temperature or shapes (14W cool-white LED, 13W warm-white LED, 18W CFL and 40W halogen globes) were measured to assess the illuminance values depending on different light characteristics in the vertical direction. Each mobile app showed different values in different light sources and the relative errors were different in the same mobile depending on the light sources (Figure B2.6). According to lighting power or colour temperature, most apps usually showed higher or lower values than the lux tester. The iPad 4s rear sensor showed a significantly larger deviation than others with a 28W Halogen globe.

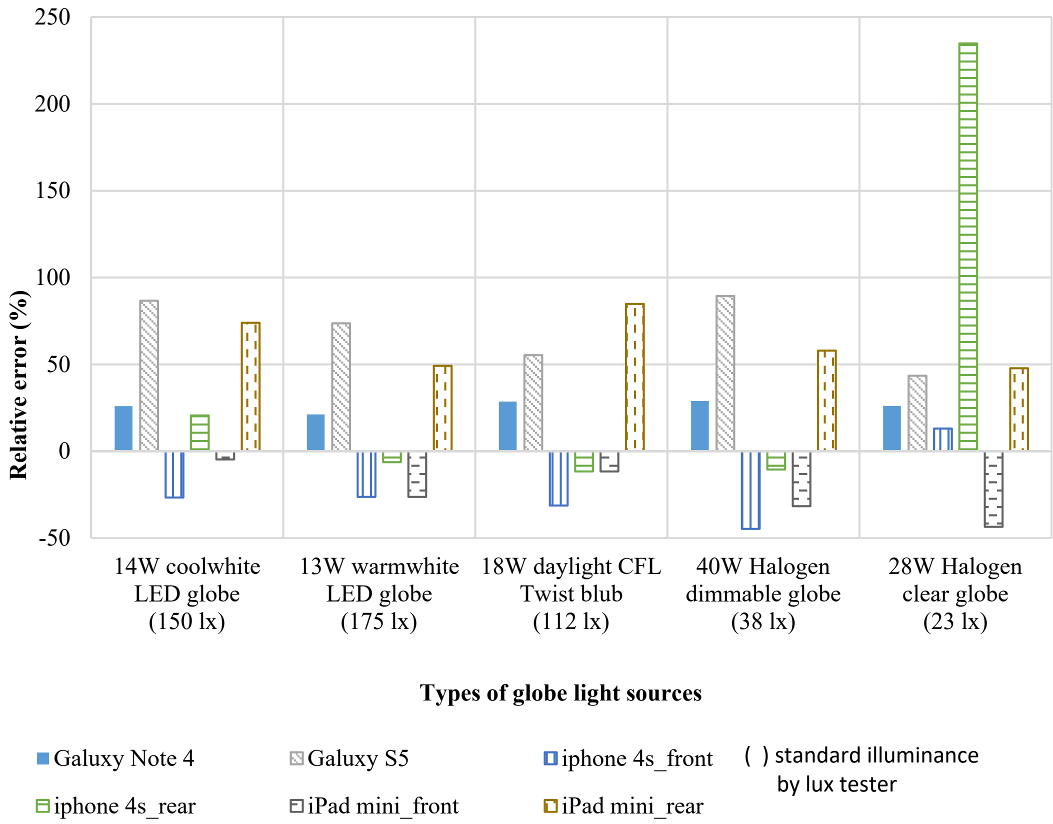


Figure B2. 6 Other light sources mounted at 1.9 m ceiling height

B2.4 Are there types of mobile phone apps that are more reliable than others?

With all illuminance values, Table B2.3 is the ranking of the mobile devices in a list to identify which mobile phones are more reliable than others when compared with the lux meter. Galaxy Note 3 showed the lowest range of the deviation and iPhone 4s rear camera sensor showed the highest range of the deviation compared the reference illuminance values. As mentioned before, iPhones and iPads showed completely different illuminances between front and rear camera sensors and furthermore, there was inconsistency in iOS devices while Android phones showed more consistent illuminance values that the values from Galaxy Note 4, S5 and Motorola Razr which were always lower than the lux meter. However, Cerqueira et al. reported that same version mobiles (iPhone 5) with iOS system showed varying illuminance values under the same conditions and Goldschmidt and Pittner stated similar variation in results (Farrier, Farrier, & Gilmour, 2006; Goldschmidt & Pittner, 2016).

Table B2. 3 The ranking of the mobile devices compared the lux meter (under vertical illuminance)

Rank	Type of mobile devices	The range of deviation (%)	The range of absolute difference	Average of deviation (%)
1	Galaxy Note 3	-18 to -29	9	-9
2	Galaxy Note 4	21 to 33	11	18
2	iPad pro rear	83 to 94	11	29
4	Motorola Razr	13 to 30	17	7
5	iPad pro front	-56 to -38	18	-15
6	iPhone 7 front	-62 to -38	24	-20
7	iPhone 7 rear	-19 to 38	57	6
8	Galaxy S5	43 to 100	67	46
9	iPhone 4s front	-65 to 15	80	-13
10	iPad mini front	-43 to 45	88	-9
11	iPad mini rear	-45 to 84	129	28
12	iPhone 4s rear	-28 to 234	262	20

B2.5 Discussion

Illuminance meters are cosine corrected and can measure a wide range of illuminance from the angular incidence of light (Hovila, Mustonen, Kärhä, & Ikonen, 2005). However, light sensors for mobile cameras installed in mobile devices can only sense the direct light radiation upon the surface of a mobile screen. Most studies have only measured the vertical illuminance of these sensors and compared their outcomes with typical lux meters. In the present tests for examining the illuminance values at various angles of directions, mobile apps showed larger deviations from the lux meters under ceiling-mounted fluorescent linear lamps than under direct vertical illuminances and the intensities of the illuminance including four ceiling mounted fluorescent lamps were lower than the levels under the only vertical illuminances (Figure B2.3 & B2.4).

According to Cerqueira et al. (2018)'s study, the higher the levels of the reference illuminance, the larger the deviations in values of the illuminance from mobile apps measured in a vertical direction. However, depending on types of light sources (e.g. shapes, powers, colour temperature, etc.), the deviations varied in this study (Figure B2.6).

From the results in Table B2.3, it appears that there might be reliable mobile apps or mobile devices which can be used to measure illuminance in the vertical direction. Galaxy Note 3 showed the lowest range of the relative error compared with the lux meter in the vertical illuminance (Table B2.3). In situations where vertical illuminance is the significant source of lighting, certain mobile apps can provide useful measurements but when the lighting is from different angles, their reliability is poor.

There are several portable dome-shaped diffusers (Lux for All or Lumu) that have been developed as attachments for mobile phones for measuring illuminance (Goldschmidt & Pittner, 2016). They were developed with the purpose of using a smartphone camera to take a high-quality picture as in a DSLR camera. These portable tools provide illuminance values and look similar to typical lux meters and thus may be used in the workplace instead of the larger professional lux meter or instead of general mobile light meter apps (Goldschmidt & Pittner, 2016). However, in this study, the focus was on the use of mobile light meter apps and did not assess these other attachment devices.

The existing studies stated that different light meter apps in the same mobile phone can show significant variations, (Cerqueira, Carvalho, & Melo, 2018; Goldschmidt & Pittner 2016). The results of this research support these outcomes.

B2.6 Conclusions

The illuminance values measured and compared between the mobile apps and the lux meter under vertical illuminance and varied illuminance situations were significantly different. Mobiles with the iOS operating system showed completely different illuminances between their front and rear camera sensors.

A mobile phone is very innovative technology to help us to do many things without the need for a range of other devices. However, the light sensor in a mobile phone was primarily developed for the use of a mobile camera and light meter apps differ from lux meters used by industry professionals in terms of the user utilization. (Liu, 2013) It is tempting to think that these free or low cost light meter apps can assess the occupational lighting environments, however, development and assessment of more reliable apps is needed before reliable use in the occupational environment.

B3. Can a mobile phone be used for blue light assessment?: preliminary experiments with a blue filter on mobile phone light sensor

Blue light can pass through a blue filter by 440 nm wavelengths and with this filter, a luminance meter can measure blue-weighted spectral radiance like a spectroradiometer (Okuno, 1988). This filter may enable blue light hazard (BLHF) function-weighted illuminance with a range of mobile apps and the lux meter. However, there is no evidence regarding a blue filter equipped on illuminance meter can penetrate blue light and show BLHF illuminance. To verify this hypothesis, a blue filter was used on the cosine corrector of a lux meter and on light sensors of mobile devices and all tests using the filter were conducted in the mock-up workstation with same vertical lighting conditions of the previous experiments.

A blue filter (HOYA company, glass type: B440, 50×50 mm) was used to measure blue light hazard (BLHF) function-weighted illuminance on a lux tester and mobile device apps.

Figure B3. 1 A blue filter and an example of the measurement of blue-weighted illuminance

B3.1 Could a blue light filter be used to assess blue light hazard?

In principle, an illuminance meter can read the blue-weighted illuminance if a blue filter transmits the area of colour blue and blocks the other colour range of the light source.

B3.2 What is different between blue light-weighted and –unweighted illuminance for the various light sources?

The illuminance values from all mobile apps and the lux meter with a blue filter were low, typically 0 to 5 lx. The iPhone 4s rear and iPad mini front camera sensors showed the range of BLHF illuminance between 13 to 60 lx compared to the range of the illuminance values between 110 to 682 lx under vertical lighting directions. The BLHF illuminances from mobile apps and the lux meter with a blue filter were almost 100 times lower than the values without the filter (Table B3.1).

Table B3. 1 BLHF illuminance with a blue filter

	Light sources							
	12W LED daylight		**14W LED Cool-white**		**13W LED Warm-white**		**42W Halogen Pearl**	
Rated Colour temperature (K)	5700		6500		3000			
Rated Lumens	9500		1400		1400		600	
Measurement Distance (cm)	120		115		100		50	
	Illuminance (lx)		Illuminance (lx)		Illuminance (lx)		Illuminance (lx)	
	without Blue filter	with Blue filter	without Blue filter	with Blue filter	without Blue filter	with Blue filter	without Blue filter	with Blue filter
Lux tester (Standard)	320	4	320	4	320	3	320	2
Samsung Note 3	259	5	216	4	397	3	203	4
Samsung Note 4	423	7	410	4	213	3	380	3
iPhone 7_front	119	1	119	1	-	-	-	-
iPhone 7_rear	258	4	320	4	-	-	-	-
iPhone 4s_front	110	0	143	0	-	-	-	-
iPhone 4s_rear	229	20	682	60	-	-	-	-
iPad mini_front	466	13	143	-	129	-	-	-
iPad mini_rear	175	13	261	-	261	-	-	-

B3.3 Conclusions

Although the outcomes using the filter were significantly lower than the actual illuminance values (Table B3.1), there is some potential for determining the blue light hazard using a simple illuminance measuring device. Further work is required to validate this approach.

Appendix C.

Attenuation of exposure to blue light using eye protection

The quality and degree of light absorption filters are very important for blocking harmful light, such as blue light or UV, which can damage on the eyes. Bruzell et al. (2007) measured the quality of eye protection filters for dental personnel who are exposed to dental curing and bleaching lamps. They reported that some blue protective filters were potentially inadequate to block exposure of intense dental curing lamps and concluded that design and marking of light protective filters should be considered for the users (Bruzell et al. 2007).

According to Hiromoto et al.' study, a deep yellow lens could absorb most blue LED light. Colour pink and blue light antireflective coating lens showed less absorption of blue light and resulted in more retinal ganglion cell damage than other orange and yellow coloured lenses (Hiromoto et al. 2016).

Appendix C was conducted to investigate effectiveness of safety glasses and sunglasses to filter out blue wavelengths.

C.1 Methods

Coloured glasses

A clear safety glasses with UV protection (3M company, PELTOR Lexa model), two pair of blue light blocking glasses (UVEX company, S1933X & S0360X models) and a general red-brown coloured sunglass with UV protection were measured (Figure C.1).

Figure C. 1 Samples of various coloured glasses used in the study ((a) clear safety glasses with UV protection, (b) Uvex blue light blocking safety glasses (S1933X), (c) Uvex blue light blocking safety glasses (S0360X), (d) sunglasses with UV protection)

Assessment and characteristics of blue light sources

Two LED downlights (DETA company, 12W dimmable coolwhite and warmwhite), dental curing lamp (BA international LTD, S/N: H12010470B) and two nail curing lamps (Gelish, 18G 36W LED and 5-45 18W LED) were used to measure the spectral radiance using a spectroradiometer (Specbos 1211 UV, JETI Germany, S/N: 2010143). The measurement distance between the light sources to the spectroradiometer was 20 cm as the worst case scenario provided by the Australian/New Zealand Standard (AS/NZS 62471, 2011) (See Figure C.2).

The emission of the light sources was evaluated in the light laboratory at the University of Adelaide using the spectroradiometer (Table C.1).

Table C. 1 Emission characteristics of the light sources used in the experiments

Measurement	Luminance (cd/m^2)	CCT (K)	Blue-weighted radiance (W/m^2sr)
DETA 12W cool-white LED downlight/DET492	75257	5672	56.5
DETA 12W warm-white LED downlight/DET490	66451	3024	22.4
BA Optima 10 (dental curing lamp)	6272	NA	114.5
Gelish 18G (36W LED nail curing lamp)	43	421	13.9
Gelish 5-45 (18W LED nail curing lamp)	130	423	39.8

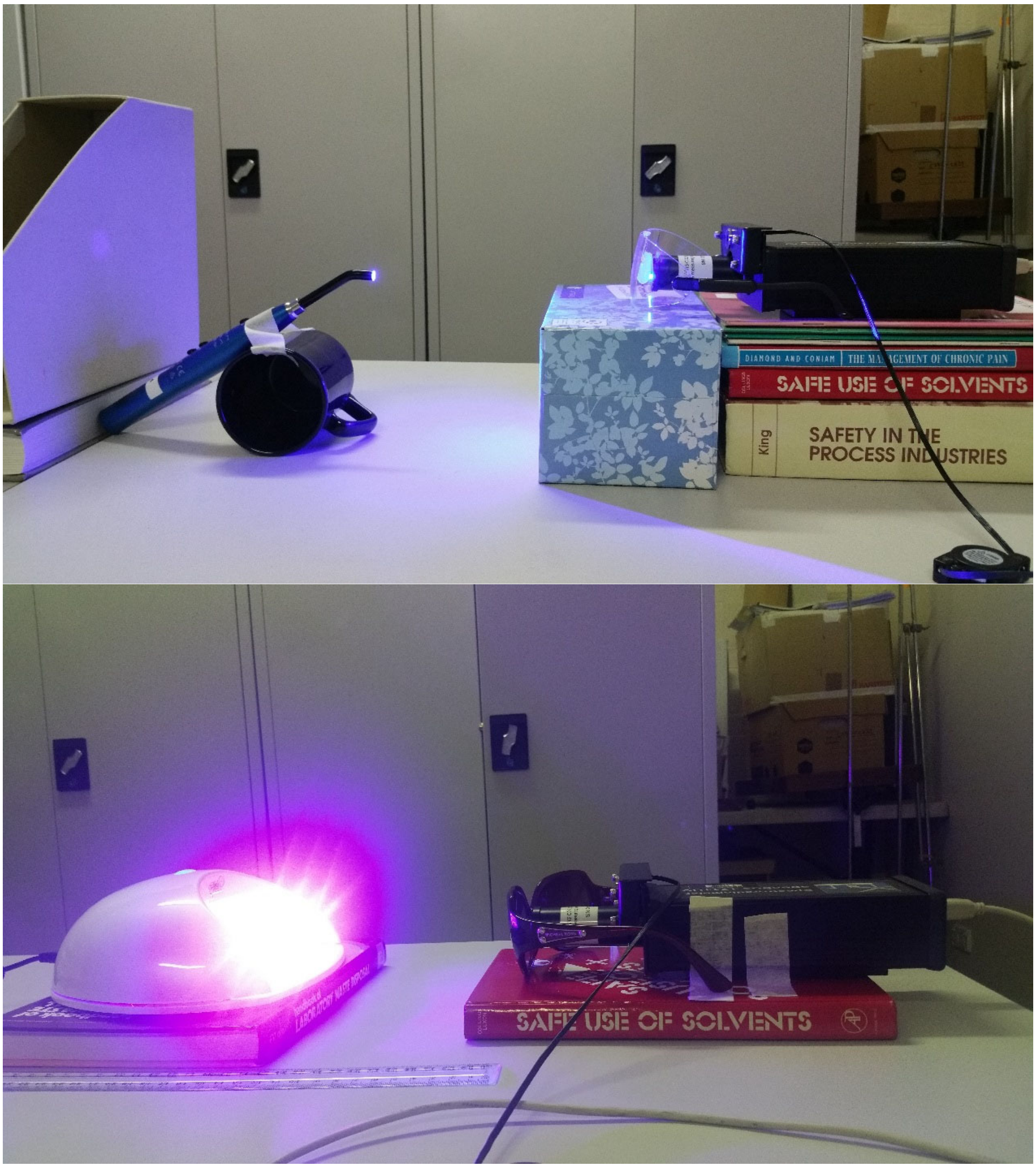


Figure C. 2 Examples measurement set-up
(a dental curing lamp and a clear safety glasses with UV protection (top), and an 18W UV LED nail curing lamp and sunglasses with UV protection (bottom))

C.2 Results

The spectral radiances (L_Bs) of four blue light sources were from 13.80 up to 116.8 W/m^{2}sr at 20 cm distances. Among these, the L_B of the dental curing lamp exceeded the maximum permissible radiance, 100 W/m^{2}sr and the 12W cool white LED downlight showed a high level of L_Bs, 73.06 W/m^{2}sr closed to the limit.

Two blue light blocking safety glasses (UVEX S1933X & S0360X) could filter most of blue wavelengths and the range of their L_Bs were 0 to 0.35 W/m^{2}sr compared to the original L_Bs ranging from 13 to 116 W/m^{2}sr. The sunglasses with UV protection could reduce the amount of the exposure to blue light up to about 50 %.

However, the results of the clear safety glasses with UV protection were in contrast with other glasses' results. The levels of L_B of the clear glasses were two times higher from the exposure to the dental curing lamp falls under the visible blue light spectrum and 18W LED nail curing lamp with a wide opening.

Depending on the opening design, L_Bs of LED nail curing lamps showed different results.

Table C.2 shows the outcomes of L_Bs of the blue light sources filtered by the protective eyewear and Figure C.3 is a bar chart that outlines the relevant figures.

Table C. 2 Comparison of L_Bs of blue light sources and blue light filtered sources

Blue light sources	L_B (W/m^{2}sr)				
	Without PPE	3M clear safety glasses	UVEX S0360X	UVEX S1933X	Sunglasses
DATA 12W LED warm white downlight	28.08	25.17	0.32	0.32	5.23
DATA 12W LED cool white downlight	73.06	66.96	0.35	0.34	13.67
LED dental curing lamp	**116.76**	**208.62**	0.00	0.00	23.71
36W LED nail lamp	13.80	9.57	0.00	0.03	1.48
18W LED nail lamp	39.93	**61.31**	0.00	0.20	5.93

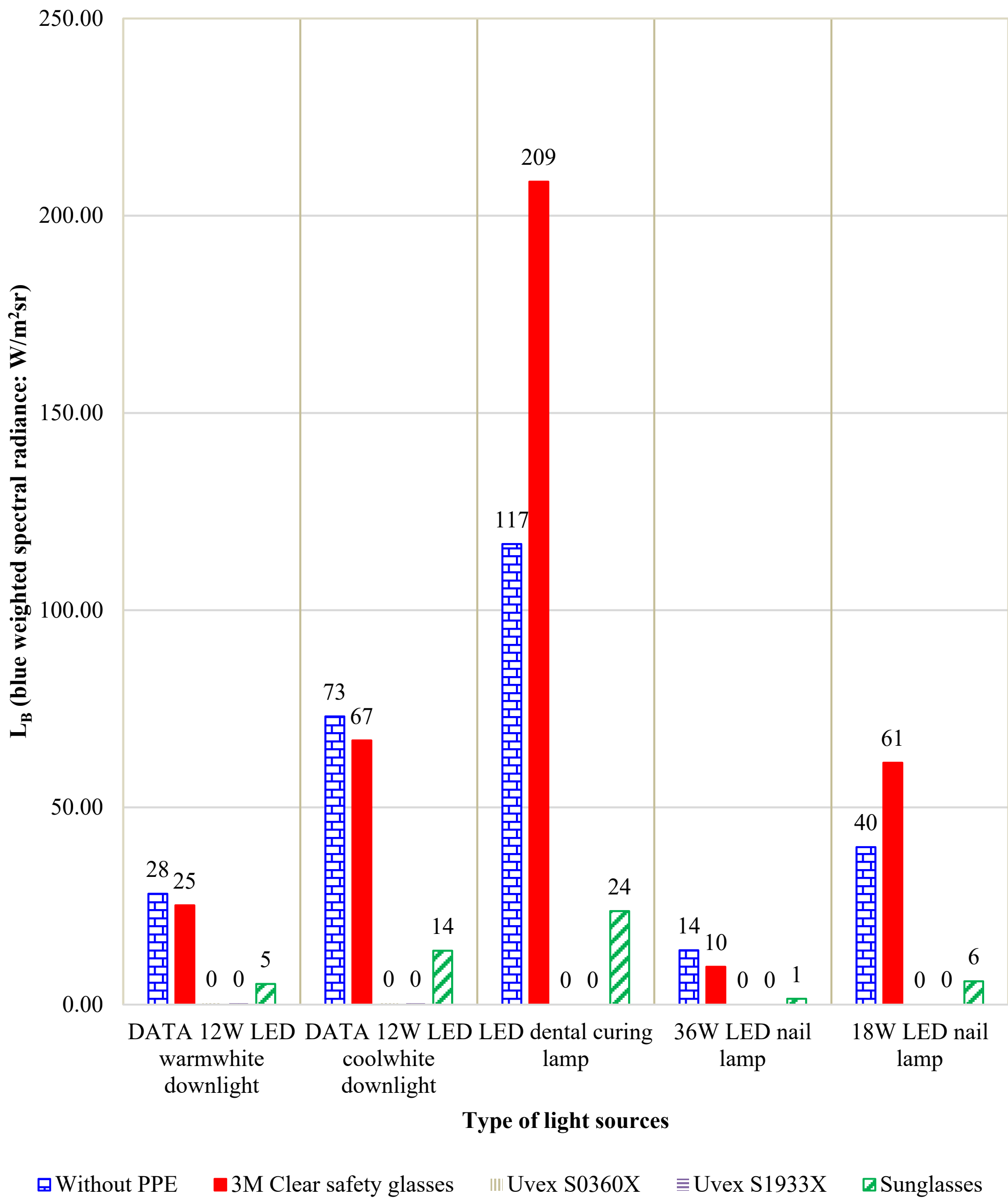


Figure C. 3 LBs of blue light sources and blue light filtered sources

C.3 Discussion and Conclusions

There are various ways to control the exposure to blue light, and protective eye glasses, which can block blue wavelengths and belong to the category of personal protective equipment, are the most common protective equipment for eye protection used in workplaces. Depending on colours and brightness of lens filters used, the amount of blue light blocked can differ and use of inappropriate eye protective equipment may cause severe eye damage (Bruzel et al. 2007, Hiromoto et al. 2016).

For these reasons, this study was conducted to determine the blue light attenuation of safety glasses.

Two orange coloured safety glasses for blocking blue wavelengths showed very low levels of the L_B, 0 – 0.3 W/m^2sr, compared to the raw L_Bs ranged 13 to 116 W/m^2sr. In addition, the red-brown coloured sunglasses with UV protection could reduce the blue light hazard up to 50 %. However, the clear safety glass with UV protection showed significantly different results. Due to the reflections on the surface of the clear UV coated glasses, the measured values of the L_Bs were *much higher* than the original L_Bs of the light sources and the L_Bs of the clear glasses under the exposure to the dental curing lamp and the UV LED nail curing lamp.

Based on the results, it appears that yellow glasses provide effective protection whereas clear glasses may not. Appropriate protective equipment should be used depending on the emission characteristic of light sources in the workplace. Further research is needed to support this information.