A comparison of illuminance values obtained from three illuminance measuring instruments

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Preface

This dissertation was written in article format in accordance with the specifications set out for the journal Occupational Health Southern Africa. The instructions to authors for this journal is found in the beginning of Chapter 3. References were set out in Vancouver style according to the International Committee the of Medical Journal where in-text references are inserted as superscript numbers after the full stop. A reference list is listed at the end of each chapter in numerical order (not alphabetically). Language and grammar were written according to United Kingdom English spelling where the only exceptions were made for names and references used.

Chapter 1 consists of a general introduction and problem statement related to the application of illuminance meters and the importance of accurate illuminance measurements in the workplace. The research aim, objectives and hypotheses of this study are included in Chapter 1. Chapter 2 comprises a literature review regarding the perception of light, including a brief introduction into light and how it is perceived; characteristics of light sources; types of lamps; lighting in the workplace, including South African occupational health and safety regulations and standards regarding illumination and the effects of adequate lighting on worker health, safety, and productivity. Photometry and the principles of light measurement and types of illuminance meters applicable to this study is discussed in Chapter 2. Chapter 3 is an article, "A comparison of illuminance values obtained from three illuminance measuring instruments", written in a format that meets the specifications of the journal Occupational Health Southern Africa. Chapter 4 is a concluding chapter that includes main findings, recommendations, a study limitation and future studies.

Authors' Contributions

This study was conducted and carried out by a research team. Contributions of each member and participating researcher are outlined in Table 1 formulated below.

Table 1: Authors' contributions

Author	**Contribution to the dissertation**
Mr. C.I Holleran	• Study design and planning. • Literature study. • Conducting of the experiment, data collection and statistical analysis. • Writing of article and formulation of recommendations.
Mr. C.J van der Merwe (Supervisor)	• Assisting with the study planning and design. • Approving the study protocol. • Construction of photometric stand • Professional guidance and recommendations. • Assisted with the interpretation of results. • Review of the dissertation.
Prof. J.L du Plessis (Co-supervisor)	• Assisting with the study planning and design. • Approving the study protocol. • Professional guidance and recommendations. • Assisted with the interpretation of results and data analysis. • Review of the dissertation.

The following is a statement from the supervisors that confirms each individual's role in the study: *I declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of CI Holleran's MHSc (Occupational Hygiene) Dissertation.*

Mr CJ van der Merwe

Prof JL du Plessis

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The right place at the right time

“The great moments of your life won't necessarily be the things you do, they'll also be the things that happen to you. Now, I'm not saying you can't take action to affect the outcome of your life, you have to take action, and you will. But never forget that on any day, you can step out the front door and your whole life can change forever. You see, the universe has a plan, kids, and that plan is always in motion. A butterfly flaps its wings, and it starts to rain. It's a scary thought, but it's also kind of wonderful. All these little parts of the machine are constantly working, making sure that you end up exactly where you're supposed to be, exactly when you're supposed to be there. The right place at the right time.” – Ted Mosby (How I met your mother, Bays & Thomas Productions & 20th Television)

Abstract

Title: A comparison of illuminance values obtained from three illuminance measuring instruments

In the field of occupational hygiene, light and the use of different lighting types have become fundamental control measures in reducing risks to health and safety while at the same time promoting increased productivity within the workplace. Illuminance meters are used in surveys to quantify the amount of light illuminating an object, surface, or general workplace to determine if illumination in the workplace complies with regulations and standards. Accurate illuminance measurement requires important considerations, such as the calibration conditions of illuminance meters, the spectral response of illuminance meters and the specific light source being measured.

The general aim of this study was to measure and compare illuminance values obtained from the Goldilux auto-ranging light meter (GL) (MIT, South Africa), Goldilux-LED auto-ranging light meter (GL-LED) (MIT, South Africa) and the Konica Minolta CL-70f illuminance meter (KM CL-70f) (Konica Minolta, Japan) under controlled laboratory conditions. The objectives of this study were: (i) to measure and compare the illuminance levels of halogen incandescent lamps (hICLs), compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) using the GL (MIT, South Africa), the GL-LED (MIT, South Africa) and the KM CL-70f (Konica Minolta, Japan); (ii) to measure and compare the illuminance levels of low-, medium-, and high-output hICLs, CFLs and LEDs, and (iii) to measure the colour correlated temperatures (CCTs) and spectral wavelengths of each of the above-mentioned light sources with the KM CL-70f illuminance meter (Konica Minolta, Japan).

The GL, GL-LED, and KM CL-70f were used to measure low-, medium-, and high-output hICLs, CFLs and LEDs precisely one metre away from the selected lamps under laboratory conditions. Background illumination in the test facility was 0 lux. Lamps were individually measured for two minutes, or until the values on the illuminance meter had stabilised. Lamp measurements were repeated three times (n=9 per lamp).

Results of the GL, GL-LED, and KM CL-70f were similar when measuring low- and medium-output hICLs. Statistically significant differences in illuminance values were observed when measuring high-output hICLs and all CFLs and LEDs. The degree to which illuminance values differed, increased when measuring lamps with higher outputs. Spectral wavelength measurements indicate that CFLs and LEDs have entirely different spectral qualities in comparison to the traditional ICL and hICLs.

To achieve accurate measurements of modern lamps, such as CFLs and LEDs, illuminance meters having a spectral response capable of measuring the entire visible spectrum should be used. Furthermore, due to the differences in spectral wavelength qualities of lamps, illuminance meters should be calibrated to measure modern lamp types such as CFLs and LEDs. There is a need for the development of regulations and standards that define which qualities of illuminance meters are required for accurately measuring light within the workplace. Currently, there is limited information considering the minimum required quality indices such as the spectral distribution qualities or the spectral mismatch factor that illuminance meters should conform to when measuring light in the workplace. The need for development of regulations and standards, as well as the application of the GL, GL-LED and KM CL-70f in the workplace were recommended. A study limitation and future studies were also discussed.

Word count: 515

Key words: Illumination, spectral mismatch, light, light meter, lux meter, incandescent lamp, compact fluorescent lamp, light emitting diodes.

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LIST OF ABREVIATIONS

AMA	American Medical Association
ANOVA	Analysis of variance
CCT	Correlated colour temperature
CFL	Compact fluorescent lamp
CIE	The International Commission on Illumination
CMOS	Complementary metal-oxide sensor
CRI	Colour rendering index
DNA	Deoxy-ribose nucleic acid
DW	Dominant wavelength
GL	Goldilux
GL-LED	Goldilux LED
hICL	Halogen incandescent lamp
ICL	Incandescent lamp
IpRGCs	Intrinsically photosensitive retinal ganglion cells
KM CL-70F	Konica Minolta CL-70f
LED	Light emitting diode
LF	Luminous flux
MIT	Marmit South Africa
MMPA	Mine Medical Professionals Association
NWU	Northwest University

OHHRI	Occupational Hygiene and Health Research Initiative
PW	Peak Wavelength
SAIOH	South African Institute of Occupational Hygiene
SANS	South African National Standards
SASOHN	The South African Society of Occupational Health Nursing Practitioners
SASOM	The South African Society of Occupational Medicine
UPS	Universal power supply
UV	Ultraviolet

Chapter 1: General introduction

1.1 Introduction

In the field of occupational hygiene, light and the use of different lighting types have become fundamental control measures in reducing risks to health and safety while at the same time promoting increased productivity within the workplace.[1,2] Safe working conditions are considered the most important aspect in the workplace, but without adequate quantity and quality of illumination present, risks to health and safety arise.[3] In South Africa, Section 8 of the *Occupational Health and Safety Act* (1993) states that: "every employer is required to provide and maintain, as far as reasonably practicable, a safe work environment that is free of risk to the health of employees."[4] Furthermore, the Environmental Regulations for Workplaces 1987, resorting under the *Occupational Health and Safety Act* (1993), states that: "Employers must illuminate every work area in their undertaking according to the illumination values listed in the Schedule specified within the regulations." This Schedule lists mandatory minimum values of maintained illuminance for specified tasks in the workplace.[5] For a workplace to comply with regulations, it is necessary to conduct routine illumination surveys, where illuminance levels are measured at various area and task dependent locations to ensure compliance with mandatory minimum values of maintained illuminance.[2]

Since the advent of artificial lighting, humans have become less reliant on natural light, with particular emphasis on lighting present in the workplace.[2] Considering the importance of light in the workplace, artificial lighting should be designed and installed to aid the visual performance of workers so that hazards to health and safety are easily detectable and avoided.[6] Traditionally, the incandescent lamp (ICL) has been the most commonly used light source in industry and domestic settings. The ICL emits light that has superior performance levels in colour rendering, colour temperatures and spectral distribution qualities in comparison to the light emitted by other lamp types.[7,8] Although the ICL is best known as the universal symbol for bright ideas and innovation, it is also notorious for being energy inefficient.[9] Due to this inefficiency, modern lamp types such as halogen ICLs (hICLs), compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) have gradually replaced the traditional ICL, rendering it obsolete.[7]

To quantify the amount of light illuminating an object, surface or general workplace, occupational hygiene practitioners use illuminance meters, also known as light or lux meters.[10] Quantifying light requires vital considerations, such as the conditions illuminance meters are calibrated under and the spectral response of the illuminance meters. In addition, the spectral qualities of the light sources being measured should also be taken into consideration.[11] The International Commission on Illumination (CIE) states that illuminance meters shall be calibrated with light from an unpolarised ICL with a colour correlated temperature (CCT) of 2856 K at a temperature of 25°C.[12] Furthermore, the photopic sensors embedded within illuminance meters should be designed to match the relative luminous efficiency function [*V(λ)*] which represents how the human eye perceives light according to photopic vision.[13,14]

The illuminance meters that are compared in this study are a Goldilux auto-ranging light meter (GL) (MIT, South Africa), a Goldilux-LED auto-ranging light meter (GL-LED) (MIT, South Africa) and a Konica Minolta CL-70f illuminance meter (KM CL-70f) (Konica Minolta, Japan). The GL is a sturdy handheld illuminance meter complemented by a solid-state sensor that is capable of measuring light within the spectral range of 410 – 680 nm. The GL is cosine and colour corrected and is calibrated to the standard ICL with a CCT of 2856 K and is capable of measuring light with an accuracy of < 3% uncertainty. The GL-LED features the same specifications as its predecessor but was specifically designed to accurately measure LEDs. The GL-LED is calibrated differently to the standard CIE unpolarised ICL. The GL-LED is calibrated against an ISO 17025 compliant Goldilux Master LED light meter using a stabilised 4000 K LED lamp and was developed for the accurate measurement of LED sources with colour temperatures ranging from 2700 – 6500 K.[15] The KM CL-70f (Konica Minolta, Japan) is a modern illuminance meter designed to aid the monitoring and control of illuminance emitted and colour properties of light sources in industrial settings.[16] The portable handheld illuminance meter features a touch screen interface and a rotating head having an embedded light receptor that measures light within the entire range of the visible spectrum of approximately 380 – 780 nm with an accuracy of < 9% uncertainty.[17,18] The KM CL-70f illuminance meter has features that allow it to measure CCT, colour rendering index, spectral wavelengths and illuminance with a cosine corrected complementary metal-oxide-semiconductor (CMOS) linear image sensor. The CMOS light sensor is a sophisticated sensor that detects spectral power distributions of light that allow the KM CL-70f illuminance meter to accurately measure modern artificial lighting such as LEDs, high intensity discharge light sources and halogen lighting.[16]

1.2 Problem statement

The ICL was banned from being imported and manufactured in South Africa since 2015, but still illuminance meters are calibrated using light from a standard unpolarised ICL with a CCT of 2856 K.[9,11,13] The AMA (2016) and Bergen (2017) states that modern lamps, such as CFLs and LEDs, have entirely different spectral properties in comparison to the previously popular ICL.[13,18] Furthermore, although photopic sensors of illuminance meters are designed to replicate the sensitivity of the *V(λ)* function, the spectral response of illuminance meters is never perfectly matched.[14] This limitation leads to errors in illuminance measurements, known as spectral mismatch errors, where the magnitude of the error depends on both the spectrum of the light source being measured and the spectral response of the illuminance meter detector.[11,13] Ouellette (1992) found that spectral mismatch errors were prevalent when measuring CFLs and more recently, Bergen (2017) states that similar mismatch errors occur when measuring LEDs.[13,20] Product specifications state that the GL and GL-LED (MIT, South Africa) have a superior accuracy of < 3% uncertainty in comparison to the < 9% uncertainty of the KM CL-70f, however, the KM CL-70f has a broader spectral range that encompasses the entire visible spectrum (380 – 780 nm). Despite illuminance meters having unique strengths and limitations, there is no indication which specifications are crucial for occupational hygiene practitioners to take into consideration when measuring illuminance in the workplace. There is currently no published literature comparing the light measuring capabilities of the GL (MIT, South Africa), GL-LED (MIT, South Africa) and KM CL-70f (Konica Minolta, Japan) when measuring different light sources.

1.3 The research aims

The general aim of this study was to measure and compare illuminance values obtained from the GL (MIT, South Africa), GL-LED (MIT, South Africa) and KM CL-70f (Konica Minolta, Japan) under laboratory conditions.

1.3.1 The research objectives

I. To measure and compare the illuminance levels of hICLs, CFLs and LEDs using the GL (MIT, South Africa), the GL-LED (MIT, South Africa) and the KM CL-70f (Konica Minolta, Japan).
II. To measure and compare the illuminance levels of low-, medium-, and high-output hICLs, CFLs and LEDs.
III. To measure the CCTs and spectral wavelengths of each of the above-mentioned light sources with the KM CL-70f illuminance meter (Konica Minolta, Japan).

1.4 Hypothesis

According to the CIE, illuminance meters are calibrated with light from an unpolarised ICL with a CCT of 2856 K.[12] hICLs have similar CCTs and spectral qualities as the traditional ICL and it is therefore hypothesised that, there are no statistically significant differences between the three illuminance meters when measuring illuminance from hICLs (Hypothesis 1).

The AMA (2016) and Bergen (2017) state that modern lamps, such as CFLs and LEDs, have entirely different spectral properties in comparison to the previously popular ICL.[13,19] Furthermore, the KM CL-70f has light measuring capabilities to measure light that encompasses the entire visible spectrum (380 – 780 nm) in comparison to the spectral range of the GL and GL-LED (410 – 680 nm).[15,16]

Due to the KM CL-70f having a spectral range capable of measuring a broader portion of the visible spectrum, it is hypothesised that the GL (MIT, South Africa) and GL-LED (MIT, South Africa) measure statistically significant lower illuminance values of CFLs when compared to the KM CL-70f (Konica Minolta, Japan) (Hypothesis 2).

Lastly, it is hypothesised that the GL (MIT, South Africa) and GL-LED (MIT, South Africa) measure statistically significant lower illuminance values of LEDs when compared to the KM CL-70f (Konica Minolta, Japan) (Hypothesis 3).

Reference list

1. Jayawardena A, Duffy D, Manahan JM. Lighting matters in industrial environments: A framework linking workplace safety to lighting quality metrics. IEEE Trans Ind Appl. 2017; 23:54-63.

2. Smith NA. Light and Lighting. In: Gardiner K, Harrington JM, editors. Occupational Hygiene. 3rd ed. Malden (Mass): Blackwell; 2005. p. 268-285.

3. Marais D. Illumination. In: Stanton DW, Kielblock J, Schoeman JJ, Johnston JR, editors. MHSC handbook on mine occupational hygiene measurements. Johannesburg (South Africa): The Mine Health and Safety Council (MHSC); 2007. p. 247-252.

4. South Africa. Occupational Health and Safety Act 85 of 1993 (Act No. 85 of 1993).

5. South African Department of Labour. Machinery and Occupational Safety Act: environmental regulations for workplaces. Government Gazette No. 268(10988), 1983 Oct 16 (published under Government Notice R 2281).

6. The South African Bureau of Standards. South African National Standards. Interior lighting, Part 1: Artificial lighting of interiors. SANS 10114-1:2005.

7. Cole M, Driscoll T. The lighting revolution: If we were experts before, we're novices now. IEEE Trans Ind Appl. 2014; 50:1509-1519.

8. Giannuzzi A, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 6, Halogen and incandescence lamps; [cited 2020 Nov 27]. p. 87-106. Available from: https://link.springer.com/content/pdf/10.1007%2F978-1-4471-6633-7.pdf.

9. Heyes J. Incandescent bulb banned… now what? EE Publishers [Internet]. 2014 Jun 16 [cited 2021 April 21] Available from: https://www.ee.co.za/article/incandescent-bulb-banned-now.html.

10. Deonarine DC. Occupational hygiene the science. 3rd ed. Bloemfontein (South Africa): Nershco (Pty) Ltd and VDH Industrial Hygiene CC; 2014. Chapter 6.5, Illumination; p. 139-174.

11. Bizjak G. LEDs and measurements – how much light source influence the measurement results. In: Proceedings of the 11th International Conference and Exposition on Electrical and Power Engineering; 2020 Oct 22-23; Lasi, Romania. New York: IEEE; 2020. p. 755-761.

12. The International Commission on Illumination Central Bureau. Characterization of the Performance of Illuminance Meters and Luminance Meters. Vienna: CIE 023/E:2013.

13. Bergen T. Photometry of lighting devices. Light Eng. 2017; 25:80-85.

14. The International Commission on Illumination Central Bureau. International Organization for Standardization. Photometry – the CIE system of physical photometry. ISO 23539-2005.

15. Marmit. Goldilux. https://www.marmit.co.za/wp-content/uploads/2018/02/Autoranging-Light-Meter.pdf (accessed 23 Mar 2020).

16. Konica Minolta Sensing Americas. CL-70F CRI Illuminance Meter, Konica Minolta sensing. https://sensing.konicaminolta.us/products/cl-70f-cri-illuminance-meter/ (accessed 28 Feb 2020).

17. Bisi O. Visible and invisible – the wonders of light phenomena [Internet]. 3rd ed. Cham (Switzerland): Springer; 2015. Chapter 2, Experiments with light; [cited 2020 Feb 17]; p. 49-99. Available from https://link-springer-com.nwulib.nwu.ac.za/content/pdf/10.1007%2F978-3-319-09825-8.pdf.

18. Wiltshire LC. Light. In: Coaton JR, Marsden AM, editors. Lamps and lighting [Internet]. New York (NY): Routledge; 1996 [cited 2020 Sep 16]. Chapter 1. Available from: https://ebookcentral-proquest-com.nwulib.nwu.ac.za/lib/northwu-ebooks/detail.action?docID=1016145.

19. American Medical Association. Human and environmental effects of light emitting diode (LED) community lighting [Internet]. The Council on Science and Public Health; 2016 [cited 2021 Jul 27] Available from: https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/AMA_Report_2016_60.pdf.

20. Ouellette M. Photometric errors with compact fluorescent sources. IEEE Trans Ind Appl. 1992; 2:1865-1867.

Chapter 2: Literature Review

2 Introduction

Chapter 2 is a literature review that comprises of information relevant to this study. Information will be presented in five sections, namely: perception of light, including a brief introduction into light and how it is perceived; characteristics of light sources; types of lamps; lighting in the workplace, including South African occupational health and safety regulations and standards regarding illumination and the effects of adequate lighting on worker health, safety, and productivity. Lastly, photometry, discussing the principles of light measurement and types of illuminance meters applicable to this study followed by final concluding remarks.

2.1 Perception of light

Light is a form of radiant energy that is essential to perform tasks and activities during everyday life.[1] In quantum physics, light is described as having characteristics of electromagnetic waves, known as visible light and particles (photons).[2,3] Photons are defined as the basic units of visible light that carry energy and have wavelength characteristics.[2] Visible light falls in a narrow portion of the electromagnetic spectrum, at wavelengths of approximately 380 – 780 nm and is detectable by the human eye.[4,5]

The human eyes are unique spheroidal structures that detect detailed visual stimuli through a sensation known as vision.[2] Vision, arguably the most dominant of the five human senses, plays a vital role in analysing colour, form, and movement of images in our surroundings .[6,7] Attributes of vision are characterised by three factors: accommodation, adaptation, and acuity. Accommodation refers to the eyes' ability to focus on an object and is accomplished by the lens adjusting until the image is in focus. Adaptation refers to the ability of the eye to adjust to the brightness of the immediate environment, and acuity refers to the ability to detect detail within a visual task.[1] Visual perception occurs when light reaches the sensing elements of the retina, known as photoreceptor cells.[7] Once light has reached the photoreceptors, neurons known as ganglion cells transmit the stimuli to the optic nerve where it is further relayed to the visual cortex in the human brain.[6] There are three types of photoreceptors located in the retina of the human eye, namely, rods, cones, and intrinsically photosensitive retinal ganglion cells (ipRGCs).[7]

2.1.1 Rods

Rods are photoreceptors that align in a band formation around the periphery of the retina and facilitate scotopic vision, which is visual perception in low light settings such as during night-time.[8] Rods detect the presence of photons but are unable to distinguish between wavelengths within the visible spectrum.[2] Therefore, rods are exceptionally sensitive to light, but do not distinguish between different colours in light.[2,6]

2.1.2 Cones

Cones are photoreceptors that are responsible for colour vision and are organised in the macula where the visual stimuli arrive after passing through the cornea and lens of the eye. Colour perception is achieved by cones distinguishing between wavelengths of photons arriving in the macula.[2] Cones facilitate photopic vision, which is visual perception where the eye adapts to levels of light during daylight settings.[8] In contrast to rods, cones are responsible for visual tasks that requires high visual acuity. Consequently, cones require more light than rods to allow for sharper and clearer image formation.[2,6] In 2016, Dowling et al. stated that a person with a retina without rods is night blind, however a person with a retina without cones is functionally blind.[6] The eye differentiates between different wavelengths within the visible spectrum and then the brain interprets these wavelengths as different colours.[4,5] As seen in Figure 1, the colours that fall into each band of the visible spectrum are: violet (380 – 450 nm), blue (451 – 475 nm), cyan (476 – 495 nm), green (496 – 570 nm), yellow (560 – 590 nm), orange (591 – 620 nm) and red (621 – 780 nm).[9] Light within the violet portion of the electromagnetic spectrum has the highest level of energy and the shortest wavelength, whereas light within the red portion of the electromagnetic spectrum has the lowest level of energy and the longest wavelength.[2]

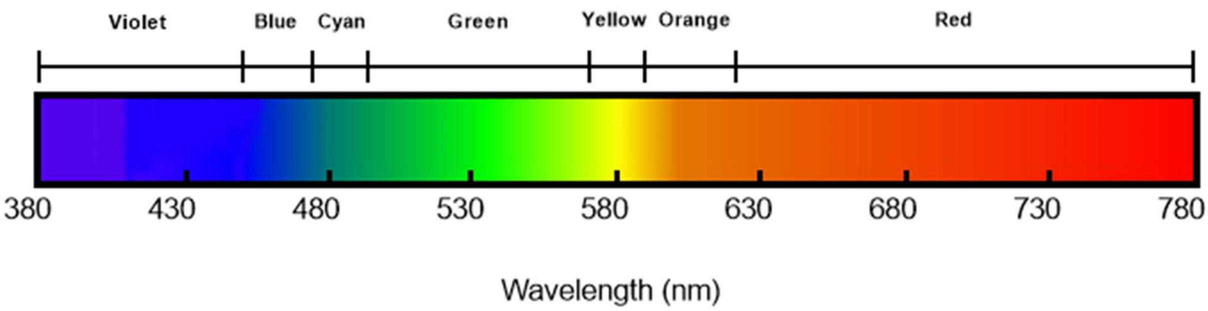

Figure 1: Specific wavelengths (nm) of colour bands interpreted within the visible spectrum.[9]

2.1.3 Intrinsically photosensitive retinal ganglion cells

IpRGCs are a relatively recent discovered subgroup of retinal ganglion cells that are responsible for non-image forming functions. While the conscious visual system provides perception of objects, the non-image forming system regulates sub-conscious effects on human behaviour and physiology such as regulating mood, alertness, sleep/wake cycles and temperature regulation.[10] Duda et al. (2020) and Aranda & Schmidt (2021) indicate that although it is currently thought that IpRGCs only play a role in non-image formation, there is growing evidence suggesting that IpRGCs affect various image formation functions such as the detection of contrast, distinction of brightness and visual response adaptation. [11,12]

Lucas et al. (2014) states that light is a potent stimulus that influences pupillary reflex responses, circadian cycle regulation, and regulation of the neuroendocrine system.[13] Such behavioural and biological effects of light are mediated by the pigment melanopsin, a complex and multifunctional photopigment that is contained within IpRGCs that are maximally sensitive to light at a wavelength of 480 nm.[11] Melanopsin responds to light even in the absence of rods and cones.[12] Lucas et al. (2014) concludes that since the discovery of IpRGCs, the current methods to measure light are incomplete. IpRGCs play an integral role in regulating behavioural and physiological states, therefore a measurement system that quantifies the effect light has on photoreceptors and their inputs needs to be investigated in the future.[13]

2.2 Characteristics of light sources

A lamp is an artificial light source that has the primary function of converting electrical energy into electromagnetic radiation, namely visible light.[14] A complete lighting unit is defined as a luminaire. Lighting units consist of one or more lamps, wiring necessary to connect the lamp to a power source, a lamp holder or bracket to hold and protect the lamps, and reflectors to direct and distribute light.[15] Characterisation of lamps involves two types of criteria: firstly, the geometrical characteristics referring to the quantity of light emitted and how it is spread, and secondly, spectral characteristics analysing the qualities of the light, such as the radiation spectrum, colour correlated temperature (CCT) and the colour rendering index (CRI).[16]

2.2.1 Geometrical characteristics

Brightness is a visual perception which describes the degree to which a surface, object or area appears to be illuminated. The brightness of a source of light does not only depend on the amount of radiation emitted, but also on the spectral composition of the radiation and the visual response function of the viewer observing it.[8] Illumination is known as the quantity of light that reaches a surface and is measured as illuminance. Illuminance is defined as the density of luminous flux (LF) present on a specific surface and is represented as lux.[17] LF is a photometric quantity that is weighted by the spectral sensitivity of the human eye to visible light. LF is known as light that is emitted from a natural or artificial light source that encounters a surface and is denoted by the symbol (Φv) and measured in lumens (lm).[1] Luminous intensity is defined as the amount of LF that is emitted per steradian in a particular direction measured in candela (cd). In this context, a steradian is a unit of measurement of a solid angle (such as a cone) and is defined as the area of a segment of a sphere that is illuminated by a source of light positioned in the centre of the sphere.[17] Candela is further defined as the luminous intensity of monochromatic radiation emitted by a source at a given direction. Irradiance is defined as the amount of radiant flux present on a surface and is measured as watt per square meter (W/m^2). Irradiance and radiant flux are the radiometric quantity equivalent of illuminance and LF respectively and are not weighted on the spectral sensitivity of the human eye to visible light. Radiant flux is defined as the amount of radiant energy that is emitted by a source of light.[18] Depending on the electrical grid a country provides, lamps typically operate at a voltage input of 120 volts (V) at a frequency of 50/60 Hertz (Hz), or 230 V at a frequency of 50/60 Hz. In South Africa, lamps that operate at 230 V at a frequency of 50/60 Hz, are predominantly authorised. Lighting equipment, such as lamps, often experience voltage fluctuations due to an unstable electrical power supply causing lamp or voltage flicker. Lamp flicker is the phenomenon of a lamp producing notably different levels of illuminance and needs to be limited to prevent uneven LF distribution.[19]

2.2.2 Spectral Characteristics

The spectral radiant energy emitted by a lamp and the principles of colorimetry form the spectral characteristics of a lamp.[16] Colorimetry is the science of quantifying and describing colour perception in humans. Colorimetric quantities classify the colour chromaticity of light by using photometric and spectral measurements.[20] The colour appearance of emitted light is known as CCT. CCT can be determined and plotted using the concepts of the CIE 1931 chromaticity diagram (Figure 2). The CIE 1931 chromaticity diagram classifies the colour chromaticity of light in terms of plotted x and y co-ordinates.[21,22] Co-ordinates on the CIE 1931 diagram are determined by the spectral distribution and radiant energy emitted by a light source. In Figure 2 all x and y co-ordinate points are bounded by what is known as the spectral locus (S). The spectral locus is represented as wavelengths of the various chromaticity points ranging from 420 – 700 nm and is connected by a line (P). Co-ordinates $x = 0.33$ and $y = 0.33$ is known as the white point (W). The white point represents the chromaticity of light in the equivalent spectrum. Point (L) indicates the Planckian locus which represents the chromaticity of a blackbody.[22] A blackbody is theoretically known as an ideal body that absorbs and subsequently emits all wavelength radiation encountering it equivalent to the colour temperature of the incoming radiation.[23,24]

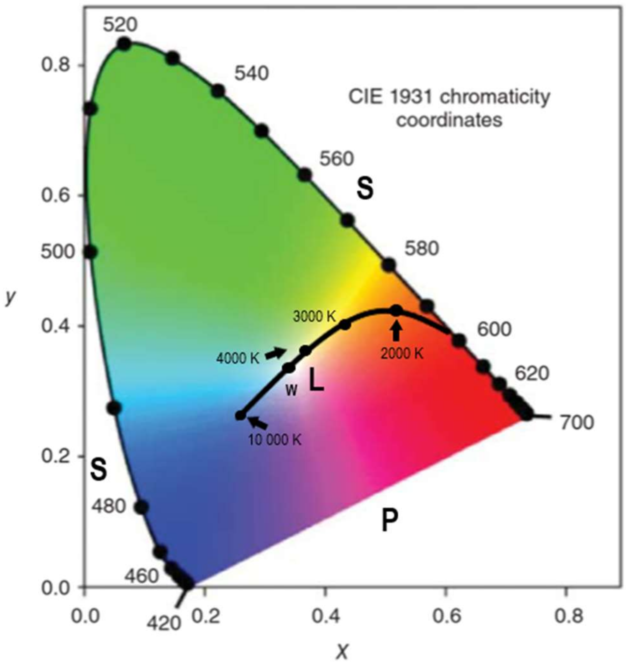

Figure 2: CIE 1931 (x, y) chromaticity diagram (adapted from Bodrogi & Khanh, 2015; SANS, 2005)[21,22].

Colour chromaticity of a heated object is known as the colour temperature. Colour temperature is defined as the colour appearance of an electromagnetic body based on its emitted temperature and is represented in kelvin (K).[17,24] Lighting with high colour temperatures emit a "cold" blue light and are represented by a higher kelvin value. On the other hand, lighting with lower colour temperatures emit a "warm" red light and are represented by a lower kelvin value.[22,23] The colour appearance of lighting used in interior spaces can be classified according to their subsequent CCT. For example, lamps with a CCT of 2700 – 3300 K will have a "warm" colour appearance, lamps with a CCT of 3300 – 5300 K will have a "warm white" to "cool white" appearance and lamps with a CCT of > 5300 K will have a "cold" appearance.[16,22]

Colour qualities of light sources are characterised by two main criteria: the colour rendering properties and its colour appearance, which are both determined by the spectral properties of the light source. The colour of an object or surface is best perceived in daylight.[22] Colour rendering is a lamp's ability to render the true colours of an object or surface as accurately and faithfully as an ideal natural light source such as daylight would.[17,24] The CRI of a light source is maximally rated at 100 (Ra), which is typically observed under both an incandescent lamp and daylight.[22] Colour attributes of light such as hue, is determined by the dominant wavelength of a light source. In this context, hue is known as the colour or shade of the emitted light and is perceived independent of the brightness or intensity of the light source.[20]

2.3 Types of lamps

The incandescent lamp (ICL) has traditionally been the most common light source used in industrial and domestic settings. Popularly commercialised by Thomas Edison in 1879, ICLs are simple sources of electrical light and have been the universal symbol for bright ideas and innovation since its inception. A resistive current causes a wire or tungsten filament to glow as an electric voltage is applied.[25] The ICL has a high-performance level in terms of its colour rendering, colour temperatures and spectral distribution in comparison to other lamps. Figure 3 displays the spectral wavelength distribution of ICLs, CFLs and LED lamps. As seen in Figure 3 ICLs have a smooth and continuous distribution across the visible light spectrum, which means they produce the best representation of daylight, better than any other light source.[26]

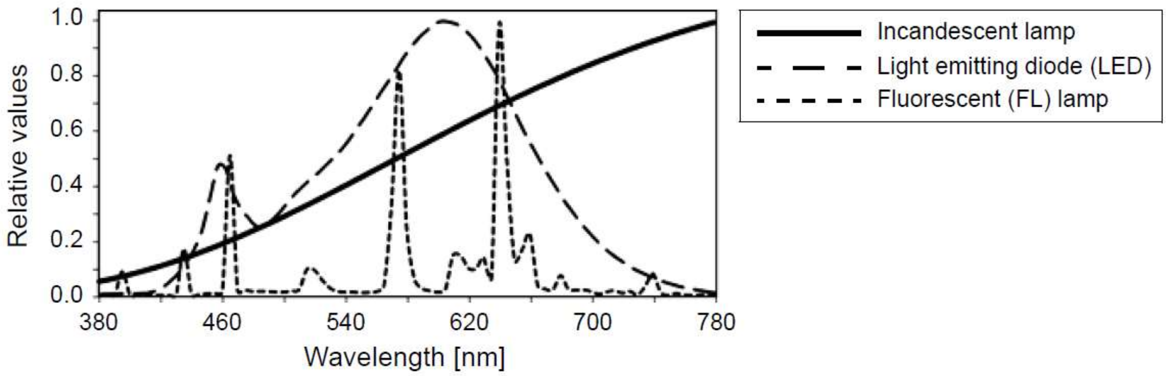

Figure 3: Spectral wavelength distribution of ICLs, CFLs and LED lamps.[27]

In South Africa, the ICL was banned from being imported and manufactured since 2015 due to newer technologies being more energy efficient.[28] Halogen ICLs (hICLs) were introduced to replace typical ICLs, featuring the same appearance in colour and classic Edison shape but with better energy efficiency and cost effectiveness.[29] Halogen lamps extend the lifespan of typical ICLs by the halogen regenerative cycle process.[26] Incorporating halogen gas in the bulb prevents the glass casing from blackening by preventing the tungsten filament from evaporating and thus increasing the lamp's lifespan.[30] Newer lighting technologies such as compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) are, however, progressively being used in place of ICLs and hICLs in industrial and domestic settings because these light sources consume less electrical energy and have a longer lifespan.[25,31]

CFLs were invented in the 1970s but they were only introduced commercially in the 1990s. In traditional fluorescent lamps, cathodes within the lamp vaporised mercury and created an ultraviolet (UV) light. Presently, the lamp is filled with krypton or argon instead of mercury, and the inner glass casing is covered by a phosphoric powder.[32] Light is produced by applying a voltage to various electrodes within the lamp which causes an energy emission that is partially transferred into visible light and partially transferred into UV radiation. UV radiation is a highly energetic form of radiation that excites the phosphoric powder lining of the inner glass tube, and this stimulation subsequently causes a fluorescent glow.[25,32] Unlike ICLs, CFLs do not have a continuous spectrum of light emission (as seen in Figure 3). CFLs display various sharp peaks in the visible spectrum depending on the fluorescent powders used within the lamp. CFLs with a CCT of 2700 K have peaks in the red partition of the visible spectrum and lamps with 6000 K will have peaks in the blue partition of the visible spectrum.[33]

An LED is a semiconductor device that emits visible light when an electric current passes through it. Although LEDs were commercially available in the 1960s, they were inefficient until the early 2000s. LEDs have become more popular as an alternative to other lamp types because of their higher efficiency (lumens per watt) and much longer lifespan.[25]

In the lighting industry, it is impossible to produce LEDs that naturally emit a white light. Currently, there are two techniques to achieve a white light emission. Firstly, by combining semiconductors with primary colours such as blue, red, and green and secondly, to include phosphoric materials within the LED casing in conjunction with a blue or UV LED light. The first technique is only useful for changing the colour appearance of LEDs to suit an environment. The second technique converts monochromatic light to white light by stimulating phosphoric materials within the LEDs semiconductor with a high energy blue light. The phosphoric material then absorbs the emitted blue light and re-emits a broad-spectrum white light.[34] Because of this, the LED semiconductor typically produces a dominant blue light falling within the narrow spectrum around 450 nm characterised by a sharp peak (as seen in Figure 3). The rest of the light emitted by LEDs forms a somewhat continuous spectrum after the peak.[33]

2.4 Lighting in the workplace

The advent of artificial lighting has made humans less dependent on natural light with particular emphasis on lighting present in the workplace.[1] In occupational hygiene, light and lighting have progressively become fundamental factors in reducing risks to health and safety while also promoting increased productivity in the workplace.[1,7] In any working environment, safe conditions are considered most important. Artificial lighting should be designed and installed to aid the visual performance of workers so that hazards are easily detectable and thus avoided.[22] Without adequate quantity and quality of illumination in the workplace, many risks to health and safety arise. Safety hazards arise due to impaired vision caused by both low levels of illumination and excessive illumination which causes glare. Glare is caused by strong contrasts between the source of illumination and the general backgrounds of the work area.[35] Direct glare affects the immediate visual field of a worker and indirect glare is illumination reflected from surfaces into the visual field of a worker. Glare negatively affects visual performance and creates visual discomfort.[22]

Accidents and injuries may also occur in the workplace if stroboscopic effects are present. The stroboscopic effect is the apparent perception/misjudgement of slowing of speed, stopping, or reversing of rotating machinery. Minimising stroboscopic effects from lighting within the workplace is paramount to avoid accidents and injuries. Fluorescent lamps, discharge lighting and LED lamps causes the stroboscopic effect due to the pulsating output of lamps operating under alternating current power supply.[22]

2.4.1 Legislation

In South Africa, Section 8 of *Occupational Health and Safety Act* (1993) states that: “Every employer is required to provide and maintain, as far as reasonably practicable, a safe work environment that is free of risk to the health of employees.” [36] Furthermore, the Environmental Regulations for Workplaces 1987, resorting under the *Occupational Health and Safety Act* (1993), states that: “Employers must illuminate every work area in their undertaking according to the illumination values listed in the Schedule specified within the regulations.” This Schedule lists mandatory minimum values of maintained illuminance for specified tasks in the workplace. Additionally, specialised lighting necessary for the performance of any type of work, whether stipulated in the Schedule or not, must be provided by the employer.[37] Illumination surveys are conducted at various task dependent locations within a workplace. Measured illuminance values are then compared to regulations to ensure compliance with mandatory minimum values of maintained illuminance.[1] In a study analysing the effects of increased illuminance levels on visual performance, it was found that increasing illuminance levels from a level below the permitted level, 200 lux, to a level of 400 lux, significantly increased the visual performance of office administrators.[38]

2.4.2 South African standards applicable to illumination

The South African National Standards (SANS) 10114-1: 2005, titled *Interior lighting, Part 1: Artificial lighting of interiors*, is an approved national standard that aims to provide guidelines and recommendations for interior workplaces that create appropriate viewing conditions and a visual environment that is free from adverse effects. SANS 10114-1 states that, although the quantity of illuminance on specific tasks is important, other factors that contribute to the quality of light should also be considered. Improved quality of light promotes visual comfort, increased efficiency throughout the work shift, and protects the workers' health and safety.[22]

Lighting installations within the workplace should be designed to assist the visual acuity of individuals performing tasks. Appropriate colour rendering of surfaces and objects increases productivity by improving recognition of fine details in tasks and visual efficiency. In the occupational setting, precise and constant colour rendering of lighting is important for work performance. For instance, cotton grading and colour matching of paints need specially designed lighting for intricate colour judgements and comparisons.[22]

2.4.3 The effects of lighting on health

High colour correlated temperatures of lamps have proven to be a useful intervention in improving productivity and well-being in the workplace by increasing alertness, visual task performance, sleep quality and improved vitality in workers. However, it is also stated that an increase in colour temperature causes a higher amount of blue light to be emitted.[39] Although blue light has many benefits within the workplace, its application should be used sporadically to prevent negative effects related to chronic exposure to blue light. Excessive and chronic exposure to blue rich light has been linked with the suppression of melatonin. Melatonin has unique properties that protects DNA damage and counteracts free radicals that can lead to the development of hormone dependent cancers such as breast and testicular cancers. Furthermore, melatonin has been known to play a role in increasing the rate of cancer cell death and in inhibiting the multiplication of cancer cells. Highly excessive night-time exposure to blue rich light can possibly lead to the development of hormonal dependent cancers through the chronic inhibition of melatonin. There is also speculation that intense blue light can cause damage to the retina and destruction of photopigments within the eye and this is known as blue-light hazard.[40] However, in the same study conducted by Pawlak (2018) it was concluded that claims of blue-light hazard are often exaggerated when referring to artificial light sources such as LEDs which were found to be safe to use.[40]

Although newer lamp types are more energy efficient and have a longer lifespan, the American Medical Association (AMA) (2016) states that both CFLs and LEDs have different spectral outputs in comparison to the previously popular ICL (as seen in Figure 2).[41] There is speculation that the change in spectral outputs of lighting within the work environment may pose health concerns.[31] IpRGCs are most sensitive to blue light radiation with wavelengths ranging from 450 – 520 nm.[31] Blue light causes an increase in alertness and delays the circadian rhythm.[13] This is caused by blue-sensitive ipRGCs sending signals to the pineal gland through what is known as the suprachiasmatic nucleus within the brain, which in turn suppresses the secretion of melatonin, known as the sleeping hormone.[31] Blue light also increases heart rate, core body temperatures, cortisol production and regulates mood.[13] The American Conference of Governmental Industrial Hygienists (2019) states that workers' health, safety, and alertness are of the utmost importance, therefore it is recommended that high intensity blue light be provided during daytime and especially night-time in order to prevent accidents and injuries relating to sleepiness and fatigue.[31] Contrarily, the AMA (2016) states that blue light used in street lighting causes a disruption in humans' circadian rhythm and neuroendocrine system.[41] Night-time exposure to blue light has been shown to cause a short-term negative effect in sleep quality along with delayed transitions in night-time physiological processes. Such processes include a decrease in body temperature, an increase in melatonin blood concentrations, and a decrease in hunger to be delayed from an earlier time to much later in the evening. The AMA (2019) recommends using LED lighting with a lower CCT in streetlights to curb circadian and physiological disruptions while also minimising potential negative health effects.[41]

2.5 Photometry: measuring light

Visible light perceived by the human eye can be measured using concepts of photometry. Photometry is the science of quantifying visible light with specific emphasis on the biological sensitivity of the human eye to different spectral wavelengths.[9,13] Occupational hygienists use instruments known as illuminance meters, also referred to as light/lux meters, to quantify the amount of light illuminating an object, surface or general workplace.[42]

2.5.1 Illuminance meters

Illuminance meters are photoelectric devices embedded with optic filters that can accurately re-enact the human eye's response to light intensity. The use of integrated optic filters in illuminance meters is known as colour correction.[1] A light measuring cell within the device converts the incoming incident light into an electronic signal that is then displayed in lux on the screen of the meter.[17] Measuring cells are cosine corrected, allowing illuminance meters to accurately measure light that meets the light sensor at various angles, which is vital especially when measuring lighting installations for street lighting, workplace, and office settings.[43]

Accuracy of illuminance meter measurements depends on operational conditions, characteristics of the instrument and properties of light sources. The International Commission on Illumination states that all illuminance meters shall be calibrated with light from an unpolarised incandescent lamp with a CCT of 2856 K at an ambient temperature of 25°C. Ambient temperature influences the spectral responsivity of the illuminance meter. Operating illuminance meters where the ambient temperature of the surrounding environment differs from the temperature used when calibrating the instrument, will cause reduced accuracy in meter readings. Recalibration of illuminance meters should occur at least every two years, at a time frame recommended by the manufacturers or in an instance where instrument performance has changed.[43]

2.5.2 Spectral mismatch errors

According to Giannini (2015) the human eye does not have the same response throughout the entire visible spectrum. The response changes depending on the wavelength of the light and the physiological and/or psychological state of the observer.[18] Due to visual response variations from person to person, to obtain precise photometric measurements, a standard representation for observers needs to be defined. The CIE developed what is known as the relative luminous efficiency curve *V(λ),* also known as the spectral luminous efficiency function, which represents how the human eye perceives light according to photopic vision.[8,44] Adapted from the CIE spectral luminous efficiency function *V(λ),* Figure 4 represents the scotopic and photopic spectral sensitivity of the human eye.[1]

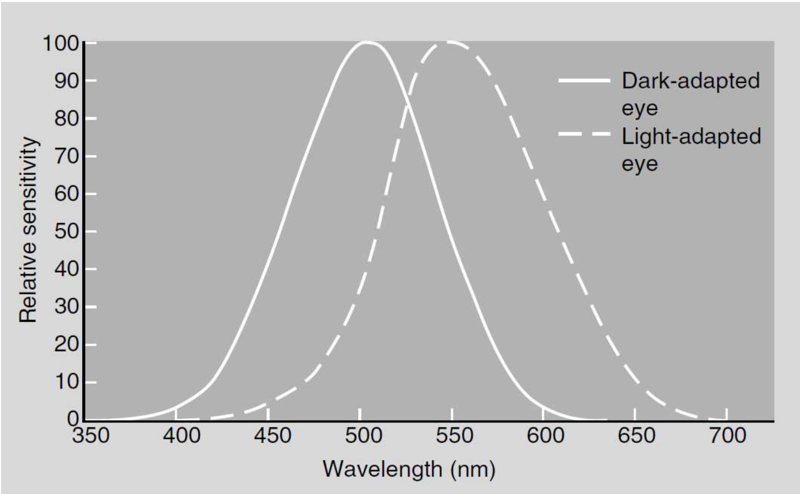

Figure 4: Scotopic and photopic spectral sensitivity of the human eye.[1]

Photopic sensors within illuminance meters are designed to match the *V(λ)* function, however, the spectral response of illuminance meters is never perfectly matched. Due to the spectral response of illuminance meters never completely matching the ideal *V(λ)* function, errors in illuminance measurements occur and are referred to as spectral mismatch errors. The magnitude of the error is dependent on the spectral response of the photodetector and the spectrum of the lamp being measured.[44] Bizjak (2020) states that illuminance meters contain a general *V(λ)* mismatch index that determines illuminance measurement uncertainty. A larger uncertainty factor will translate to a less accurate illuminance meter and measurements with a higher degree of error/uncertainty.[45]

Measuring light in workplace environments requires important considerations, such as what conditions the illuminance meters are calibrated under and the spectral qualities of the light sources being measured.[45] Bergen (2017) states that modern lamps, such as LEDs, have an entirely different wavelength spectrum in comparison to the incandescent lamp used to calibrate illuminance meters.[44] In a study conducted by Bizjak (2020) it was found that even when using spectral mismatch correction factors, illuminance measurement errors were observed when measuring LEDs and CFLs with a known applied lux.[45] Furthermore, it was found that measuring light sources with a higher CCT often led to higher illuminance measurements in comparison to measuring sources with a lower CCT. This indicated that illuminance meters are more appropriate to produce reliable results when measuring the red portion of the luminous efficiency $V(\lambda)$ function of human vision in comparison to the blue portion. In an older study, Ouellette (1992) found that illuminance meters produced photometric errors of up to 11% when measuring CFLs.[46] To ensure accurate measurements of modern light sources such as LEDs and CFLs, it is necessary to calibrate the illuminance meter being used as closely as possible to the light source being measured.[45]

2.5.3 Comparison of illuminance meters

Illuminance meters investigated in this study are the Goldilux (GL) auto-ranging light meter (MIT, South Africa), the GL-LED auto-ranging light meter (MIT, South Africa) and the Konica Minolta (KM) CL-70f (Konica Minolta, Japan).

2.5.3.1 The GL auto-ranging light meter (MIT, South Africa)

The GL auto-ranging light meter (MIT, South Africa) is a sturdy handheld illuminance meter with a solid-state sensor capable of measuring visible light at a spectral range of 410 – 680 nm. The light measuring cell in the GL is a silicon photodiode sensor that is calibrated with light from an unpolarised incandescent lamp with a CCT of 2856 K. The GL is cosine and colour corrected and can measure light sources with an accuracy of <3% uncertainty. This device uses older technology to determine illumination levels in industries such as mining, agriculture, architecture, street lighting and many more.[47]

2.5.4 The GL-LED auto-ranging light meter (MIT, South Africa)

The GL-LED auto-ranging light meter is an ISO 17025 certified illuminance meter specifically calibrated for accurate measurement of LED sources and is embedded with a solid-state sensor capable of measuring visible light at a spectral range of 410 – 680 nm. This instrument is not calibrated to light from an unpolarised ICL with a CCT of 2856 K. Instead, the GL-LED is calibrated against an ISO 17025 compliant GL Master LED light meter using a stabilised 4000 K LED lamp. The GL-LED is cosine and colour corrected and can measure light sources with an accuracy of <3% uncertainty. The GL-LED was specifically developed for accurately measuring LEDs with a colour temperature ranging from 2700 K to 6500 K.[47]

Table 1: Specifications of the three illuminance meters used in this study. [47,48]

Illuminance meters			
Instrument	GL 	GL-LED 	KM 
Range (lux)	1–200 000	1–200 000	1–200 000
Spectral range (nm)	410–680	410–680	380–780
Cosine correction factor (f_2)	<1.5%	<1.5%	<6%
Accuracy ($V\lambda$ Match)	<3% uncertainty	<3% uncertainty	<9% uncertainty
Measurement parameters	Illuminance in Lux (cosine and colour corrected)	Illuminance in Lux (cosine and colour corrected)	Illuminance in Lux (cosine and colour corrected), CRI, CCT, dominant λ, spectral irradiance and colour deviation
CCT range	Not specified	2700 to 6500 K	1563 to 100 000 K
Price range (R)	± 7000	± 7000	± 50 000

2.5.5 The KM CL-70f (Konica Minolta, Japan)

The KM CL-70f (Konica Minolta, Japan) is an illuminance meter used for monitoring and control of illumination and colour of light sources in industrial settings. The portable handheld device features a touch screen interface and a rotating head that has an embedded light receptor that measures visible light in the spectral range of 380 – 780 nm. The KM CL-70f illuminance meter has features that allows it to measure CCT, colour rendering index, spectral wavelengths and illuminance with a cosine corrected complementary metal-oxide-semiconductor (CMOS) linear image sensor. The CMOS light sensor is a sophisticated sensor that detects spectral power distributions of light that allows the KM CL-70f illuminance meter to accurately measure modern lamp types such as LEDs, high intensity discharge light sources and halogen lighting. This modern illuminance meter is intended to be used to evaluate illuminance, spectral distribution, colour temperature and rendering indices of lighting used in indoor agriculture, street lighting, specialised office lighting and in industry.[48]

2.6 Conclusion

Lighting within workplace environments is used to promote productivity, improve health, wellbeing, and safety.[7] Currently LEDs and CFL lamps dominate the lighting market and are used in most homes and industrial workplaces, thus rendering the traditional ICL and halogen lamp outdated.[45] Despite ICLs being banned years ago, illuminance meters are still calibrated using light from a standard unpolarised incandescent lamp with a CCT of 2856 K.[44-45] The AMA (2016) and Bergen (2017) state that modern lamps, such as LEDs and CFLs, have entirely different spectral properties in comparison to the previously popular ICL.[41,44] Important factors such as the spectral response of illuminance meters, the conditions illuminance meters were calibrated under and the light source being measured should be considered when measuring light.[43,45] In previous studies, Ouellette (1992) and Bizjak (2020) found that illuminance measurements in CFLs and LEDs were inaccurate due to spectral mismatch errors.[45,46] It is important to emphasise that accurate field measurement of light within domestic and industrial workplaces is crucial to provide an appropriate living and working environment as well as to facilitate efficient and safe work performance.[7,45] There is currently no available information investigating the comparison of light measuring capabilities of the GL auto-ranging light meter (MIT, South Africa), GL-LED auto-ranging light meter (MIT, South Africa) and KM CL-70f (Konica Minolta, Japan) when measuring various light sources.

Reference list

1. Smith NA. Light and Lighting. In: Gardiner K, Harrington JM, editors. Occupational Hygiene. 3rd ed. Malden (Mass): Blackwell; 2005. p. 268-285.

2. Bartholomew EF, Martini FH, Nath JL. Fundamentals of Anatomy & Physiology [Internet]. 11th ed. Harlow (UK): Pearson Education; 2017. Chapter 17, The special senses; [cited 2020 Sep 16]; p. 613-652. Available from: https://ebookcentral-proquest-com.nwulib.nwu.ac.za/lib/northwu-ebooks/detail.action?docID=5186130.

3. Henriksen EK, Angell C, Vistnes AI, Bungum B. What is light? Sci Educ. 2018; 27:81-111.

4. Bisi O. Visible and invisible – the wonders of light phenomena [Internet]. 3rd ed. Cham (Switzerland): Springer; 2015. Chapter 2, Experiments with light; [cited 2020 Feb 17]; p. 49-99. Available from https://link-springer-com.nwulib.nwu.ac.za/content/pdf/10.1007%2F978-3-319-09825-8.pdf.

5. Wiltshire LC. Light. In: Coaton JR, Marsden AM, editors. Lamps and lighting [Internet]. New York (NY): Routledge; 1996 [cited 2020 Sep 16]. Chapter 1. Available from: https://ebookcentral-proquest-com.nwulib.nwu.ac.za/lib/northwu-ebooks/detail.action?docID=1016145.

6. Dowling JE, Dowling JL, Dowling JLJ. Vision: How it works and what can go wrong [Internet]. 1st ed. London, Cambridge (UK): MIT Press; 2016 [cited 2020 Nov 3]. Available from: https://ebookcentral-proquest-com.nwulib.nwu.ac.za/lib/northwu-ebooks/reader.action?docID=4460296.

7. Jayawardena A, Duffy D, Manahan JM. Lighting matters in industrial environments: A framework linking workplace safety to lighting quality metrics. IEEE Trans Ind Appl. 2017; 23:54-63.

8. The International Commission on Illumination Central Bureau. International Organization for Standardization. Photometry – the CIE system of physical photometry. ISO 23539-2005.

9. Fontani D, Francini F, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 10, Building Glasses and Skylights: Optical Characterization; [cited 2020 Nov 29]. p. 167-193. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

10. Do MTH, Kang SH, Xue T, Zhong H, Liao HW, Bergles DE, et al. Photon capture and signalling by melanopsin retinal ganglion cells. Nature. 2009; 457:281-287.

11. Duda M, Domagalik A, Feuer PO, Krzysztynska-Kuleta O, Beldzik E, Smyk MK, et al. Melanopsin: from a small molecule to brain functions. Neurosci Biobehav Rev. 2020; 113:190-203.

12. Aranda ML, Schmidt TM. Diversity of intrinsically photosensitive retinal ganglion cells: circuits and functions. Cell Mol Life Sci. 2021; 78:889-907.

13. Lucas RJ, Peirson SN, Berson DM, Brown TM, Cooper HM, Czeisler CA, et al. Measuring and using light in the melanopsin age. Trends Neurosci. 2014; 37:1-9.

14. Forster R. Lighting – types of lamps and lighting. In: Stellman JM, editors. Encyclopaedia of occupational health and safety. 4th ed. Geneva (Switzerland): International labour organization; 1998. p. 2-12.

15. Mercatelli L, Giannini A, Sani E. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 3, Photometric and colorimetric tests; [cited 2020 April 27]. p. 39-63. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

16. Mercatelli L, Giannini A. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 4, Characteristics of light sources; [cited 2020 April 25]. p. 65-76. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

17. Jennings M. Lighting. In: Reed S, Pisaniello D, Benke G, Burton K, editors. Principles of occupational health & hygiene. Crows Nest (Australia): Allen and Unwin; 2013. p. 420-443.

18. Giannini A. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 1, Radiometric and photometric quantities and laws; [cited 2021 Mar 30]. p. 1-22. Available from: https://link.springer.com/content/pdf/10.1007%2F978-1-4471-6633-7.pdf.

19. Institute of Electrical and Electronical Engineers. Recommended practice for measurement and limits of voltage fluctuations and associated light flicker on AC power systems. IEEE standard 1453-2004.

20. Giannini A, Mercatelli L. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 2, Colorimetric quantities and laws; [cited 2020 April 25]. p. 23-37. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

21. Bodrogi P, Khanh TQ. The human visual system and its modelling for lighting engineering. In: Khanh TQ, Bodrogi P, Vinh QT, Winkler H, editors. LED lighting technology and perception [Internet]. Weinheim (Germany): Wiley-VCH, 2015. [cited 2021 Jul 27] p. 7-47. Available from: https://ebookcentral.proquest.com/lib/northwu-ebooks/detail.action?docID=1874137#.

22. The South African Bureau of Standards. South African National Standards. Interior lighting, Part 1: Artificial lighting of interiors. SANS 10114-1:2005.

23. Farini A. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 5, Color rendering of light sources; [cited 2021 April 1]. p. 77-87. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

24. Konica Minolta [Internet]. CRI illuminance meter: CL-70F operating manual. Available from: https://image.cotecno.cl/2020/01/Haga-clic-aqu%C#3%AD-para-el-Manual-del-CL-70F..pdf (accessed 5 Feb 2021).

25. Cole M, Driscoll T. The lighting revolution: If we were experts before, we're novices now. IEEE Trans Ind Appl. 2014; 50:1509-1519.

26. Giannuzzi A, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 6, Halogen and incandescence lamps; [cited 2020 Nov 27]. p. 87-106. Available from: https://link.springer.com/content/pdf/10.1007%2F978-1-4471-6633-7.pdf.

27. Fryc I, Tabaka P. The influence of different photometric observers on luxmeter accuracy for LEDs and FLs lamps measurements. Opt Appl. 2019; 49:345-354.

28. Heyes J. Incandescent bulb banned… now what? EE Publishers[Internet]. 2014 Jun 16 [cited 2021 April 21] Available from: https://www.ee.co.za/article/incandescent-bulb-banned-now.html.

29. Crown Reader. So, the incandescent bulb is on its way out … what now. Sparks Electrical News [Internet]. 2014 Aug 1 [cited 2021 April 21]. Available from:http://www.crown.co.za/reader/sparkselectricalnews/2014/August/files/assets/common/downloads/page0026.pdf.

30. Thumann A, Metha DP. Handbook of energy engineering [Internet]. Lilburn (GA): Fairmont Press; 2012 [cited 2021 May 04]. 78 p. Available from: : https://ebookcentral.proquest.com/lib/northwu-ebooks/reader.action?docID=3239080.

31. American Conference of Governmental Industrial Hygienists. TLVs® and BEIs®: Threshold limit values for chemical substances and physical agents & biological exposure indices. 7th ed. 2019. Cincinnati, OH: ACGIH Worldwide; 2019. 239-241 p.

32. Reggiani A, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 7, Fluorescent lamp and discharge lamp; [cited 2020 Nov 29]. p. 107-125. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

33. van Bommel W. Incandescent replacement lamps and health. Light Eng. 2011; 19:8-14.

34. Reggiani A, Farini A. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 8, LEDs and use of white LED for lighting; [cited 2020 Jul 27]. p. 127-149. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

35. Marais D. Illumination. In: Stanton DW, Kielblock J, Schoeman JJ, Johnston JR, editors. MHSC handbook on mine occupational hygiene measurements. Johanesburg (South Africa): The Mine Health and Safety Council (MHSC); 2007. p. 247-252.

36. South Africa. Occupational Health and Safety Act 85 of 1993 (Act No. 85 of 1993).

37. South African Department of Labour. Machinery and Occupational Safety Act: environmental regulations for workplaces. Government Gazette No. 268(10988), 1983 Oct 16 (published under Government Notice R 2281).

38. Zakerian A, Yazdanirad S, Gharib S, Azam K, Zare A. The effect of increasing illumination on operators’ visual performance in the control-room of a combined cycle power plant. Ann Occup Environ Med. 2018; 30:1-7.

39. Mills PR, Tomkins SC, Schlangen LJM. The effect of high correlated colour temperature office lighting on employee wellbeing and work performance. J Circadian Rhythms. 2007; 5:1-9.

40. Pawlak A. Evaluation of the hazard caused by blue light emitted by LED sources. In: Proceedings of the 7th Lighting Conference of the Viseegrad Countries; 2018 Sep 18-20; Trebic, Czech Replublic. New York: IEEE; 2018. p. 1-6.

41. American Medical Association. Human and environmental effects of light emitting diode (LED) community lighting [Internet]. The Council on Science and Public Health; 2016 [cited 2021 Jul 27] Available from: https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/AMA_Report_2016_60.pdf.

42. Deonarine DC. Occupational hygiene the science. 3rd ed. Bloemfontein (South Africa): Nershco (Pty) Ltd and VDH Industrial Hygiene CC; 2014. Chapter 6.5, Illumination; p. 139-174.

43. The International Commission on Illumination Central Bureau. Characterization of the Performance of Illuminance Meters and Luminance Meters. Vienna: CIE 023/E:2013.

44. Bergen T. Photometry of lighting devices. Light Eng. 2017; 25:80-85.

45. Bizjak G. LEDs and measurements – how much light source influence the measurement results. In: Proceedings of the 11th International Conference and Exposition on Electrical and Power Engineering; 2020 Oct 22-23; Lasi, Romania. New York: IEEE; 2020. p. 755-761.

46. Ouellette M. Photometric errors with compact fluorescent sources. IEEE Trans Ind Appl. 1992; 2:1865-1867.

47. Marmit. Goldilux. https://www.marmit.co.za/wp-content/uploads/2018/02/Autoranging-Light-Meter.pdf (accessed 23 Mar 2020).

48. Konica Minolta Sensing Americas. CL-70F CRI Illuminance Meter, Konica Minolta sensing. https://sensing.konicaminolta.us/products/cl-70f-cri-illuminance-meter/ (accessed 28 Feb 2020).

CHAPTER 3 MANUSCRIPT: A COMPARISON OF ILLUMINANCE VALUES OBTAINED FROM THREE ILLUMINANCE MEASURING INSTRUMENTS

Instructions for authors (as stated via https://ohsa.scholasticahq.com/for-authors)

Occupational Health Southern Africa

Occupational Health Southern Africa is the official mouthpiece of four occupational health practitioner societies serving Southern Africa: The South African Society of Occupational Medicine (SASOM), the South African Society of Occupational Health Nursing Practitioners (SASOHN), the Southern African Institute for Occupational Hygiene (SAIOH), and the Mine Medical Professionals Association (MMPA). The Journal is accredited with the South African Department of Higher Education and Training and is listed on African Index Medicus. Its objectives are to keep practitioners up to date with the latest occupational healthcare research and workplace-related legislation, with an emphasis on Southern Africa.

Requirements and format for submission of a manuscript

In addition to complying with the Uniform Requirements for Manuscripts Submitted to Biomedical Journals (updated name: Recommendations for the Conduct, Reporting, Editing, and Publication of Scholarly Work in Medical Journals), all articles should conform to the style requirements for publication in the Journal, which are indicated hereafter.

General requirements

- Scientific writing style, as well as good grammar, must be used.
- Content must be organised in a logical sequence.
- Articles must be relevant and scientifically significant.
- In the case of research and review articles, the methodology must be sound.

Style requirements

- The manuscript must be written in Microsoft Word format.
- Use Arial, size 11 font and 1.5 line spacing.
- Margin widths should be 2.54 cm all around.
- Round percentages accurately to 1 decimal point.
- Include leading zeros, e.g., $p < 0.05$, not $p < .05$.
- Scientific measurements must be expressed in SI units.

- Abbreviations and acronyms should only be used if absolutely necessary and must be defined on first use, but not in the abstract.
- Only proper names should have capital letters.
- Quotation marks should only be used for direct quotes.
- Other than in Tables and Figures, footnotes must not be used.
- Pages should be numbered consecutively.

References

- All statements should be appropriately referenced.
- References should be set out in the Vancouver style according to the International Committee of Medical Journal Editors: http://www.nlm.nih.gov/bsd/uniform_requirements.html.
- References should be inserted in the text as superscript numbers, after the stop, and listed at the end of the article in numerical order (not alphabetically).
- Only approved abbreviations of journal titles should be used.
- References must be of good quality (use primary sources from peer reviewed journals wherever possible).
- Personal communication and unpublished observations may be cited in the text, but not in the reference list.
- The accuracy of references is the author's responsibility.

Examples

1. Rose ME, Huerbin MB, Melick J, Marion DW, Palmer AM, Schiding JK, et al. Regulation of interstitial excitatory amino acid concentrations after cortical contusion injury. Brain Res. 2002;935(1-2):40-6.

2. Halpern SD, Ubel PA, Caplan AL. Solid-organ transplantation in HIV-infected patients. N EnGL J Med. 2002 Jul 25;347(4):284-7.

3. Murray PR, Rosenthal KS, Kobayashi GS, Pfaller MA. Medical microbiology. 4th ed. St. Louis: Mosby; 2002.

4. Harnden P, Joffe JK, Jones WG, editors. Germ cell tumours V. Proceedings of the 5th Germ Cell Tumour Conference; 2001 Sep 13-15; Leeds, UK. New York: Springer; 2002.

A comparison of illuminance values obtained from three illuminance measuring instruments

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Word count: 4063 (word count excludes the abstract, tables, figures, and references)

Key words: Illumination, spectral mismatch, light, light meter

Abstract

Background: Illuminance meters are used to quantify the amount of light illuminating an object, surface, or general workplace to determine if illumination in the workplace complies with regulations and standards. Accurate illuminance measurement requires important considerations, such as the calibration conditions of illuminance meters, the spectral response of illuminance meters and the specific light source being measured.

Objective: The aim of this study was to measure and compare illuminance values obtained under laboratory conditions with the Goldilux auto-ranging light meter (GL), Goldilux-LED auto-ranging light meter (GL-LED) and Konica Minolta CL-70f (KM CL-70f) illuminance meter**.**

Methods: The GL, GL-LED, and KM CL-70f were used to measure low-, medium-, and high-output halogen incandescent lamps (hICLs), compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) precisely one metre away from the outer glass casing of the selected lamps.

Results: Results of the GL, GL-LED, and KM CL-70f were similar when measuring low- and medium-output hICLs. Substantial differences in illuminance values were observed when measuring high-output hICLs and all CFLs and LEDs.

Conclusion: Statistically significant differences were observed between illuminance values measured using the GL, GL-LED and KM CL-70f from hICLs, CFLs and LEDs. This indicates that to achieve accurate illuminance measurements, illuminance meters that have a spectral response capable of measuring the entire visible spectrum, and which is calibrated to measure modern lamps, should be used. Furthermore, there is a need for the development of regulations and standards that define the qualities of illuminance meters required for accurately measuring light within the workplace.

Word count: 250

3 Introduction

Light is a form of radiant energy necessary to see and perform tasks and activities during the course of everyday life. The advent of artificial lighting has made humans less dependent on natural light with particular emphasis on lighting present in the workplace.[1] Although often overlooked, the use of artificial lighting has progressively become fundamental in reducing risks to health and safety while also promoting increased productivity in the workplace.[1,2]

The incandescent lamp (ICL) has historically been the most commonly used light source in domestic and industrial settings.[3] ICLs are simple sources of electrical light and have been the universal symbol for bright ideas and innovation since its inception.[4] The light emitted from ICLs are unrivalled in terms of colour rendering, colour temperature and spectral distribution quality, however, ICLs are also the least energy efficient sources of artificial light.[3] Due to this inefficiency, many governments have opted to phase out the use and manufacturing of traditional ICLs.[4] Following the gradual phasing out of ICLs in other countries, ICLs were banned from being imported and manufactured in South Africa since 2015 due to newer technologies being more energy efficient.[3,5] Newer lighting technologies such as halogen ICLs (hICLs), compact fluorescent lamps (CFLs) and light emitting diodes (LEDs) have been employed in place of traditional ICLs in industrial and domestic settings because these light sources consume less electrical energy and have a longer lifespan.[4,6]

In the field of occupational hygiene, illuminance meters—also referred to as light/lux meters—are used to quantify the amount of light illuminating an object, surface, or general workplace, in order to determine if the lighting in an occupational environment complies with regulations and standards.[7] In South Africa, Section 8 of the *Occupational Health and Safety Act* (1993) states that: “every employer is required to provide and maintain, as far as reasonably practicable, a safe work environment that is free of risk to the health of employees”.[8] Furthermore, the Environmental Regulations for Workplaces 1987, resorting under the *Occupational Health and Safety Act* (1993), states that: “Employers must illuminate every work area in their undertaking according to the illumination values listed in the Schedule specified within the regulations.” This Schedule lists mandatory minimum values of maintained illuminance for specified areas and tasks in the workplace.[9]

Accurate measurement of light in workplace environments requires important considerations, such as the conditions illuminance meters are calibrated under, the spectral response of illuminance meters and the spectral qualities of the light source being measured.[10,11] The human eye does not have the same visual response throughout the entire visible spectrum as the response changes depending on the spectral wavelength of light and the physiological and/or psychological state of the observer.[12] Due to visual response variations from person to person, the International Commission on Illumination (CIE) developed the relative luminous efficiency curve [*V(λ)*], also known as the spectral luminous efficiency function, which represents how the human eye perceives light according to photopic vision.[13,14] Photopic sensors of illuminance meters are designed to imitate the *V(λ)* to achieve precise photometric measurements that simulates the response of the human eye to visible light. However, the spectral response of illuminance meters is never perfectly matched to the *V(λ)*. Due to the spectral response of illuminance meters never completely matching the ideal *V(λ)*, errors in illuminance measurements occur and are named spectral mismatch errors. The magnitude of the error is dependent on the spectral response of the photodetector and the spectrum of the lamp being measured.[13]

The American Medical Association (AMA) (2016) and Bergen (2017) state that modern lamps, such as LEDs and CFLs, have entirely different spectral properties in comparison to the previously popular ICL.[13,15] Newer lighting technologies have rendered traditional ICLs obsolete, however, despite being banned many years ago, illuminance meters are still calibrated with light from a standard unpolarised ICL with a colour correlated temperature (CCT) of 2856 K.[7,11] Due to the difference in the spectral response of the photodetectors used in illuminance meters and the differences in the spectrum of light sources being measured, spectral mismatch errors in illuminance measurements may occur.[13] There is currently no published literature comparing the light measuring capabilities of the Goldilux auto-ranging light meter (GL) (MIT, South Africa), Goldilux-LED auto-ranging light meter (GL-LED) (MIT, South Africa) and Konica Minolta CL-70f (KM CL-70f) (Konica Minolta, Japan) when measuring different light sources.

The aim of this study was to measure and compare the illuminance values under laboratory conditions of hICLs, CFLs and LEDs obtained with the GL (MIT, South Africa), the GL-LED (MIT, South Africa) and the KM CL-70f (Konica Minolta, Japan).

3.1 Materials and method

Illuminance levels of three different lamp types were measured under laboratory conditions from the 8th of February 2021 to the 13th of March 2021 using a GL (MIT, South Africa), GL-LED (MIT, South Africa) and a KM CL-70f (Konica Minolta, Japan). Quantitative spectral wavelengths and colour correlated temperatures (CCTs) of three lamp types were measured using the KM CL-70f (Konica Minolta, Japan) illuminance meter.

3.1.1 Illuminance meters

The GL (MIT, South Africa) is a sturdy handheld illuminance meter with a solid-state sensor capable of measuring visible light within the spectral range of 410 – 680 nm. The embedded light measuring cell is a silicon photodiode sensor that is calibrated with light from an unpolarised ICL with a CCT of 2856 K. The GL is cosine and colour corrected and can measure light sources with an accuracy of < 3% uncertainty.[16]

The GL-LED is an illuminance meter specifically calibrated for accurate measurement of LED sources and is embedded with a solid-state sensor capable of measuring visible light at a spectral range within the spectral range of 410 – 680 nm. The GL-LED is calibrated against an ISO 17025 compliant Goldilux Master LED light meter (MIT, South Africa) using a stabilised 4000 K LED lamp. The GL-LED is cosine and colour corrected and can measure light sources with an accuracy of < 3% uncertainty.[16]

The KM CL-70f (Konica Minolta, Japan) is a portable handheld illuminance meter that features a touch screen interface and a rotating head having an embedded light receptor that measures visible light within the spectral range of 380 – 780 nm with an accuracy of < 9% uncertainty. The KM CL-70f illuminance meter has the capabilities to measure CCT, colour rendering index, spectral wavelengths and illuminance with a cosine corrected complementary metal-oxide-semiconductor (CMOS) linear image sensor that is calibrated with light from an unpolarised ICL with a CCT of 2856 K.[17]

3.1.2 Lamp preparation

Each lamp type was represented by three lamps of different light output levels, namely low, medium, and high. Three low-, three medium- and three high-output lamps of each lamp type (2900 K hICLs, 4000 K CFLs and 6500K LEDs) were purchased and used in this study (a total of 27 lamps). Lamp seasoning, also referred to as lamp ageing, was conducted before experimentation commenced. The lamp seasoning process included the operation of the selected lamps for a duration of 1% of the lamp's total rated lifespan.[18] This process is essential before taking illuminance measurements of new and unseasoned lamps as there is a fluctuation in the amount of light emitted from the lamps up until they have been operated for 1% of the lamp's total rated lifespan.[19] To prevent the phenomenon of lamp flicker, a Mecer ME-3000-GTU universal power supply (UPS) (Mecer, South Africa) was used to regulate and measure the voltage output (V) and frequency (Hz) of power supplied to the lamps being used. This ensured that light output from the lamp did not fluctuate due to an unstable electricity supply.

3.1.3 Site preparation

An illuminance stand with an approximate height of 1.98 metres was assembled. The CIE states that light testing should take place in a draught-proof room with air-movement not exceeding 0.25 m/s.[14] Furthermore, the CIE and South African National Standards state that lamps are designed to operate at an optimum ambient temperature of 25°C and standard ambient temperatures for light testing should be at a temperature of 25°C (with a tolerance interval of ± 1.2 °C) and with a maximum relative humidity of 65%.[11,14,20,21]

The ambient conditions within the test facility were kept constant throughout the experimentation phase. Doors and windows of the test facility were closed to prevent air-movement. A split-unit air conditioning unit was used to maintain the temperature constant at 25°C at a low fan speed setting. A TSI VelociCalC with TSI hotwire anemometer attachment (TSI, Minnesota, USA) was used to measure air-movement within the test facility and to verify that air-movement did not exceed 0.25 m/s during the experimental phase. A QUESTemp 34 thermal environment monitor (TSI QUEST, Minnesota USA) was used to measure the dry-bulb temperature and to verify that the relative humidity did not exceed 65%. The QUESTemp 34 (TSI QUEST, Minnesota USA) was placed next to the illuminance stand and allowed to acclimate for 30 minutes after it was switched on, and left on, for the duration of the experiment.

3.1.4 Illuminance measurement preparation

Once the standard ambient conditions were met, the illuminance meters were placed inside the room and given an hour to stabilise in the ambient environment.[11] The Illuminating Engineering Society (2008) states that before illuminance measurements are taken, the selected lamp should first be operated long enough to stabilise in the ambient environment.[22] Before illuminance measurements were taken, the selected lamp was switched on for 15 minutes to acclimate to the ambient conditions. Lamps were selected randomly by making use of a Latin square design method.[23]

3.1.5 Measurement methodology

After the selected lamp and illuminance meters had acclimated to the ambient conditions, all other light sources were switched off. Background illumination in the test facility was 0 lux which ensured that illuminance meter readings were not affected by external light sources. Each lamp was measured individually by each illuminance meter precisely one metre away from the outer glass casing of the lamp. Illuminance meters were attached to a tripod stand at a horizontal plane during lamp measurement. Lamps were individually measured for two minutes, or until the values on the illuminance meter had stabilised. Lamp measurements were repeated three times (n=9 per lamp). The GL (MIT, South Africa) and the GL-LED (MIT, South

Africa) measured the illuminance levels and in addition to illuminance, the KM CL-70f (Konica Minolta, Japan) measured the spectral wavelengths and CCTs of the lamps used in this study.

3.1.6 Statistical analysis

GraphPad Prism 8 (GraphPad Prism, version 8, Graphpad Software Inc., USA) was used for statistical analysis and the creation of graphs. Basic descriptive statistical analysis, including means, standard deviations, and range were calculated. The D'Agostino and Pearson omnibus test was used to test for normality, and it was found that the data was normally distributed, where α (alpha) = 0.05. Welch's analysis of variance (ANOVA) test was used to determine any significant variation in the covariate ambient conditions such as dry-bulb temperature (ºC), output voltage (V) and output frequencies (Hz). A one-way ANOVA test, followed by Tukey's multiple comparisons post hoc test, was used to determine if there were any significant differences between illuminance levels of the different lamp types as measured by the various illuminance meters. A p-value, of $p \leq 0.05$ was considered as being slightly statistically significant, $p \leq 0.01$ moderately statistically significant, $p \leq 0.001$ highly statistically significant and $p \leq 0.0001$ very highly statistically significant.

3.1.7 Ethics

This study was approved by the Health Research Ethics Committee (HREC) of the North-West University (NWU) Potchefstroom Campus (ethics number: NWU-00444-20-A1).

3.2 Results

Covariate ambient conditions namely dry-bulb temperature (ºC), output voltage (V) and output frequency (Hz) had no significant influence on the results obtained [Welch's ANOVA measurement parameters ($p > 0.05$)]. Additional descriptive statistics for illuminance values obtained for each illuminance meter are found in Table S1 in the supplementary materials.

3.2.1 Spectral qualities of lamps

Figure 1 represents the spectral wavelengths of hICLs, CFLs and LEDs, where peak wavelength (PW) and dominant wavelength (DW) were measured using the KM CL-70f. Spectral measurements obtained of low-output hICLs, recorded a PW of 779.78 ± 0.67 nm, and 780 ± 0.00 nm for medium- and high-output hICLs. The DWs of hICLs were 584 ± 0.00 nm.

PWs of 545 ± 0.00 nm were recorded for all three output levels of CFLs. A DW of 578.67 ± 0.50 nm was found for low-output CFLs, 578 ± 0.50 nm for medium-output CFLs and 576.33 ± 0.50 nm for high-output CFLs.

Spectral measurements obtained for low-output LEDs, recorded a PW of 454.11 ± 0.33 nm, 450.78 ± 0.67 nm for medium-output LEDs and 454 ± 0.00 nm for high-output LEDs. DWs of 487 ± 0.71 nm, 494.78 ± 1.64 nm and 489.44 ± 0.73 nm were recorded for, low-, medium-, and high-output LEDs respectively.

Figure S1 (supplementary materials), includes quantitative CCT measurements obtained using the KM CL-70f. The CCT of lamps rated, by the manufacturer, of hICLs, CFLs and LEDs were 2900 K, 4000 K and 6500 K respectively.

Low-output hICLs measured a CCT of 2656.56 ± 16.99 K, 2721.00 ± 7.31 K for medium-output hICLs and of 2731.56 ± 7.83 K for high-output hICLs.

The measurement of low-output CFLs resulted in a CCT of 3858.44 ± 33.54 K, 3824.89 ± 42.53 K for medium-output CFLs and 3908.67 ± 27.61 K for high-output CFLs.

Lastly, low-output LED measurements resulted in a CCT of 6577.11 ± 41.24 K, 6142.78 ± 40.48 K for medium-output LEDs and 6385.00 ± 35.31 K for high-output LEDs.

3.2.2 Illuminance levels of hICLs

Figure 2 (A, B and C) illustrates illuminance values of low- (28-Watt), medium- (42-Watt) and high-output (70-Watt) hICLs respectively. Illuminance levels of low-output hICLs measured with the GL resulted in a mean of 18.01 ± 3.21 lux, 18.24 ± 3.40 lux using the GL-LED and 19.89 ± 3.56 lux using the KM CL-70f. No significant differences in lux values were found between the three illuminance meters ($p > 0.05$).

Results of medium-output hICLs obtained with the GL were 30.96 ± 2.33 lux, 32.50 ± 2.73 lux with the GL-LED and 35.51 ± 3.49 lux using the KM CL-70f. No significant differences in lux values were found between the GL-LED and the KM CL-70f ($p > 0.05$). Moderately significant differences were found between the GL and the KM CL-70f ($p \leq 0.01$). Finally, high-output hICLs illuminance levels were 53.83 ± 1.04 lux using the GL, 56.77 ± 1.10 lux using the GL-LED and 61.44 ± 1.70 lux using the KM CL-70f. Highly significant differences were found between the GL and the GL-LED ($p \leq 0.001$). Very highly significant differences were found between the GL and the KM CL-70f, and between the GL-LED and the KM CL-70f ($p \leq 0.0001$).

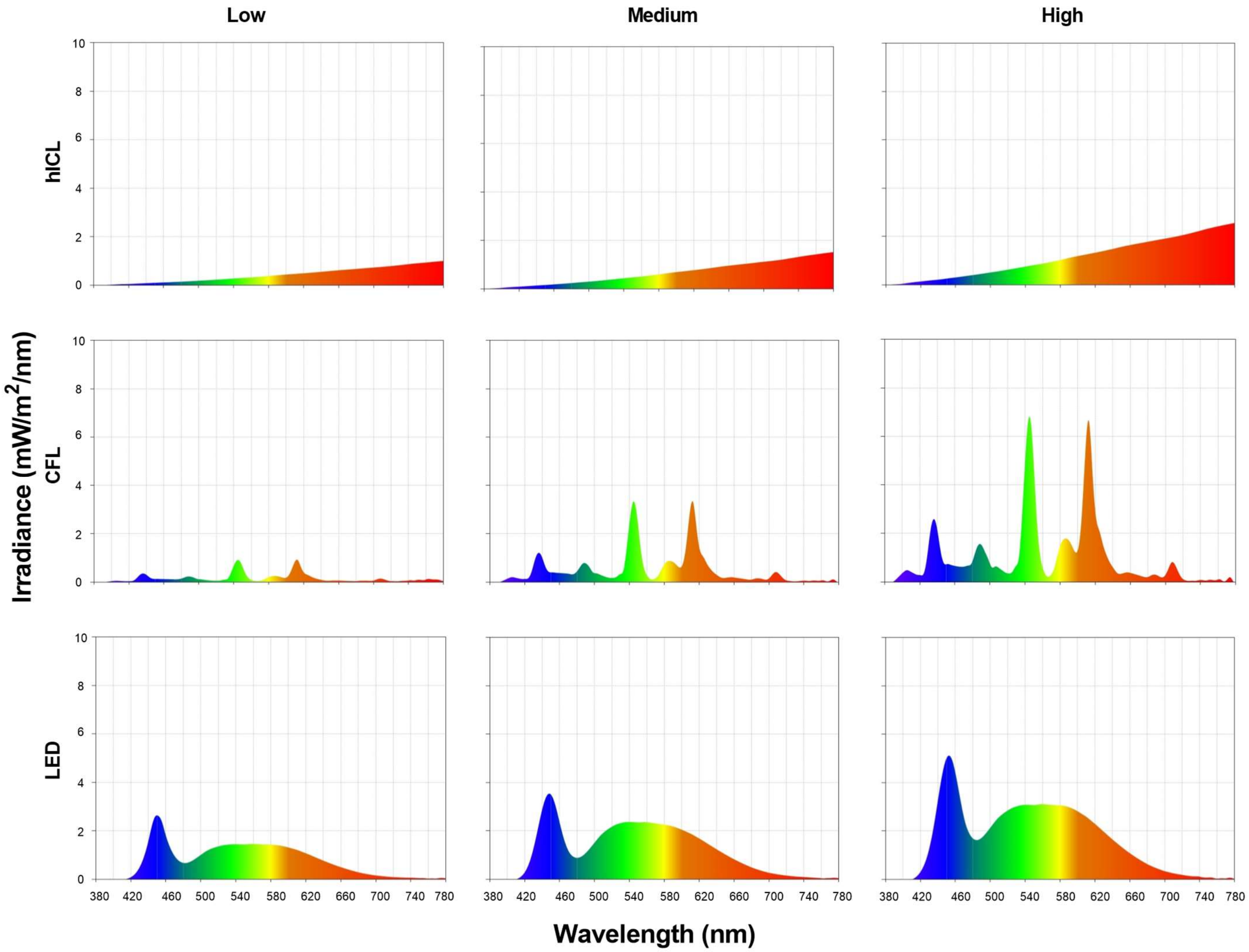

Figure 1: Spectral wavelengths of low-, medium-, and high-output hICLs, CFLs and LEDs, measured using the KM CL-70f (Konica Minolta, Japan)

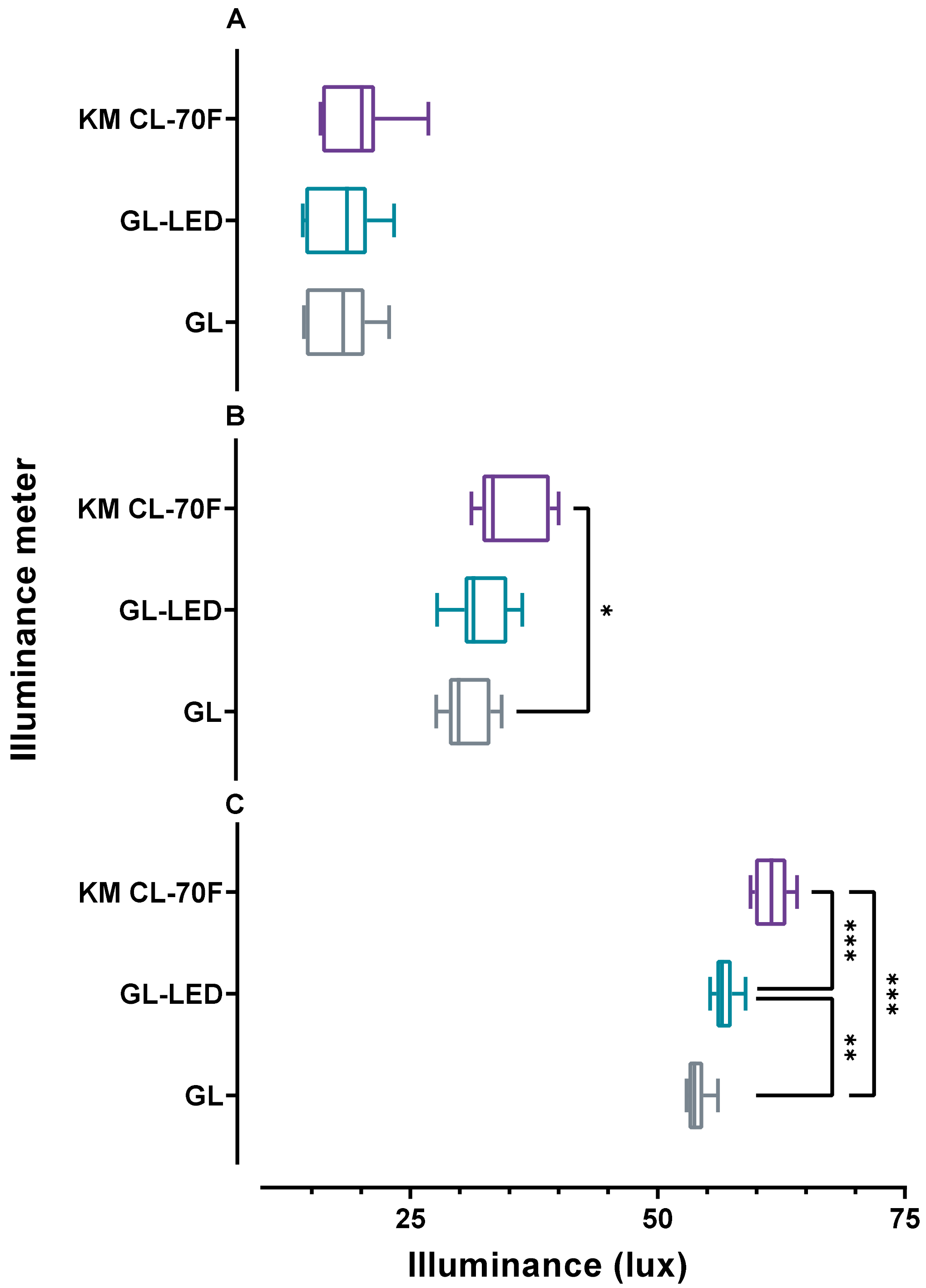

Figure 2: Illuminance levels (lux) of (A) low-, (B) medium- and (C) high-output hICLs measured by the GL, GL-LED, and KM CL-70f respectively. The box and whisker diagram consists of minimum, 25% percentile, median, 75% percentile and maximum. * Indicates significant differences ($p \leq 0.01$), ** Indicates significant differences ($p \leq 0.001$), and *** Indicates significant differences ($p \leq 0.0001$) between illuminance meters.

3.2.3 Illuminance levels of CFLs

Figure 3 (A, B and C) illustrates illuminance values of low- (9 Watt), medium- (20 Watt) and high-output (45 Watt) CFLs. Illuminance levels of low-output CFLs, using the GL, resulted in a mean of 22.68 ± 0.64 lux, 23.76 ± 0.53 lux using the GL-LED and 25.70 ± 0.48 lux using the KM CL-70f. Moderately significant differences were found between the GL and the GL-LED ($p \leq 0.01$). Very highly significant differences were found between the GL and the KM CL-70f, and between the GL-LED and the KM CL-70f ($p \leq 0.0001$).

Results obtained for medium-output CFLs using the GL were 53.31 ± 1.67 lux, 57.09 ± 2.32 lux using the GL-LED and 62.10 ± 2.65 lux using the KM CL-70f. Moderately significant differences were found between the GL and the GL-LED ($p \leq 0.01$). Highly significant differences were found between the GL-LED and the KM CL-70f ($p \leq 0.001$). Very highly significant differences were found between the GL and the KM CL-70f ($p \leq 0.0001$).

Lastly, high-output CFLs illuminance levels were 111.50 ± 4.21 lux using the GL, 120.1 ± 4.19 lux using the GL-LED and 126.7 ± 3.16 lux using the KM CL-70f. Highly significant differences were found between the GL and the GL-LED ($p \leq 0.001$). Moderately significant differences were found between the GL-LED and the KM CL-70f ($p \leq 0.01$). Very highly significant differences were found between the GL and the KM CL-70f ($p \leq 0.0001$).

3.2.4 Illuminance levels of LEDs

Figure 4 (A, B and C) illustrates illuminance values obtained for low- (5 Watt), medium- (9 Watt) and high-output (14 Watt) LEDs respectively. Illuminance levels measured for low-output LEDs using the GL resulted in a mean of 66.02 ± 1.07 lux, 71.07 ± 1.83 lux using the GL-LED and 74.81 ± 1.65 lux using the KM CL-70f. Very highly significant differences were found between the GL and the GL-LED, and between the GL and the KM CL-70f ($p \leq 0.0001$). Highly significant differences were found between the GL-LED and the KM CL-70f ($p \leq 0.001$).

Results obtained for medium-output LEDs using the GL were 110.10 ± 2.16 lux, 119.20 ± 2.29 lux using the GL-LED and 124.30 ± 2.40 lux using the KM CL-70f. Very highly significant differences were found between the GL and the GL-LED, and between the GL and the KM CL-70f ($p \leq 0.0001$). Highly significant differences were found between the GL-LED and the KM CL-70f ($p \leq 0.001$). High-output LEDs illuminance levels were 166.30 ± 2.47 lux using the GL, 179.30 ± 2.33 lux using the GL-LED and 187.40 ± 2.19 lux using the KM CL-70f. Very highly significant differences were found between the GL the GL-LED and the KM CL-70f ($p \leq 0.0001$).

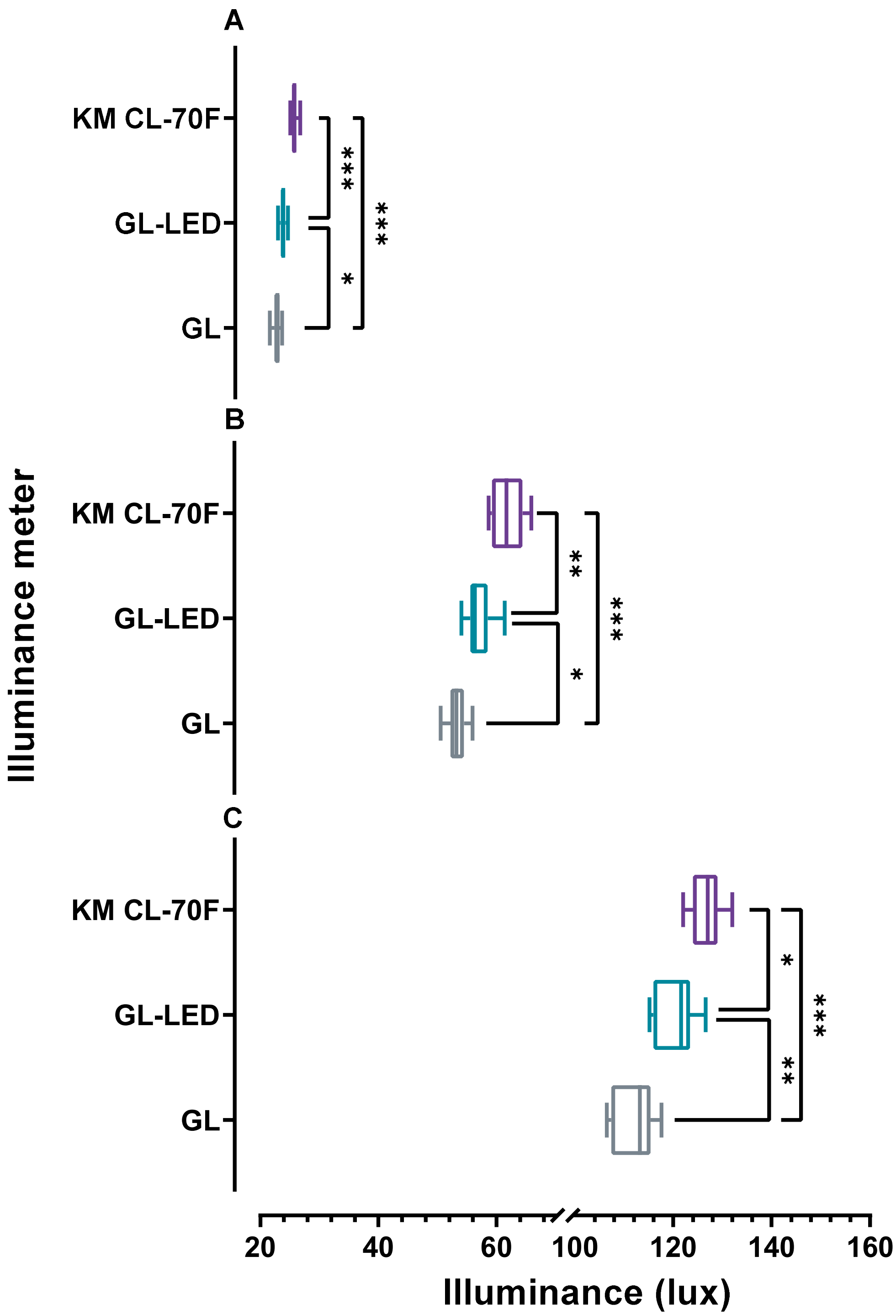

Figure 3: Illuminance levels (lux) of (A) low-, (B) medium- and (C) high-output CFLs measured by the GL, GL-LED, and KM CL-70f respectively. Refer to Figure 2 for information regarding components of the box and whisker diagram and statistically significant differences.

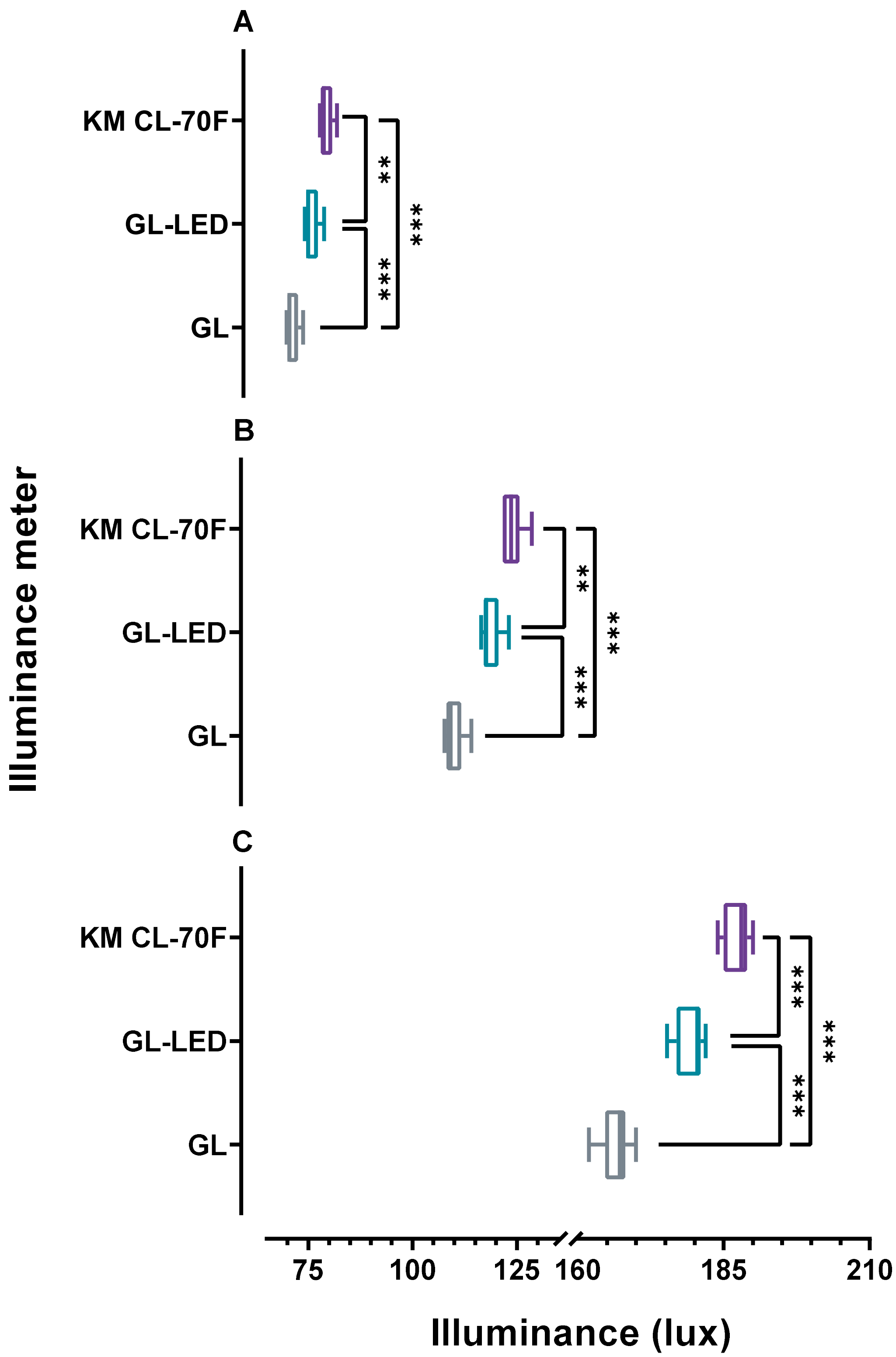

Figure 4: Illuminance levels (lux) of (A) low-, (B) medium- and (C) high-output LEDs measured by the GL, GL-LED, and KM CL-70f respectively. Refer to Figure 2 for information regarding components of the box and whisker diagram and statistically significant differences.

3.3 Discussion

There are three important considerations to take into account when measuring illuminance namely, the spectral qualities of the light source(s) being measured, the conditions illuminance meters are calibrated under and the spectral response of the illuminance meter.[10,11] In Figure 1, hICLs have a continuous and smooth wavelength spread across the visible spectrum which is identical to the spectral wavelength distribution of traditional ICLs.[3] PW measurements, obtained for all three output levels of hICLs, were found to lie within the red spectral band of the visible spectrum as seen in Figure 1.[24] Unlike hICLs, CFLs displayed various narrow and sharp peaks within the visible spectrum, as suggested by van Bommel (2011).[25] The PWs of CFLs were found within the green spectral bands of the visible spectrum, with a smaller peak in the red, and a small peak in the blue spectral bands of the visible spectrum. LEDs presented a prominent PW within the 450 nm blue spectral band of the visible spectrum, followed by a partially continuous distribution of visible light throughout the rest of the visible spectrum.[25] Colour hue appearance determined by the DW indicated that hICLs and CFLs had similar DWs while LEDs had substantially lower DWs. These findings confirm that CFLs, and LEDs have entirely different spectral wavelength qualities in comparison to not only the traditional ICL, but also hICLs.[13]

Under the specific conditions in this study, the KM CL-70f measured different CCTs than the manufacturer rated specifications. Differences in CCT ranged between 169-245 K for hICLs, 81-142 K for CFLs and 15-360 K for LEDs. The comparison of illuminance values found that in most cases, there were highly significant differences in measuring different lamp types. The least significant differences were observed when measuring hICLs, followed by CFLs. The most significant differences between illuminance meters were observed when comparing LEDs. This indicates that higher CCTs could lead to an increase in uncertainty of illuminance measurements when comparing illuminance meters.

When comparing all the illuminance meters, it was observed that the KM CL-70f measured the highest illuminance values, followed by the GL-LED. The lowest values were observed with the GL. The differences between spectral composition and illuminance levels were investigated when measuring different output levels. When comparing the differences between the spectral composition of different light output levels, such as low-, medium-, and high-output in Figure 1, it was found that the spectral composition was almost identical for each lamp type (i.e. hICL, CFL or LED). Despite having different light outputs, no substantial differences in spectral qualities can be observed between the different light output levels. However, results indicated that significance in differences between illuminance levels, increased in lamps with a higher output.

There was no statistically significant difference in illuminance values obtained from low-output hICLs which indicates that all three illuminance meters provide corresponding results when measuring low-output hICLs. However, despite the GL and the KM CL-70f being calibrated with an unpolarised ICL with a CCT of 2856 K, significant differences in illuminance values were observed (Figure 2) when comparing medium- and high-output hICLs which have similar CCTs as the lamp used to calibrate these illuminance meters (2721.00 ± 7.31 K and 2731.56 ± 7.83 K respectively).

In comparison to results obtained from low- and medium-output hICLs, substantially significant differences between illuminance meters were observed in high-output hICLs, and low-, medium-, and high-output CFLs and LEDs. Several studies have found that illuminance errors were prevalent when measuring CFLs and LEDs due to spectral mismatch errors in illuminance meters.[10,26] When comparing the specifications of each illuminance meter, the GL and GL-LED have a low spectral mismatch uncertainty of < 3% where-as the KM CL-70f has a higher spectral mismatch uncertainty of < 9%. However, the GL and GL-LED can only measure light within a limited range of the visible spectrum of 410 – 680 nm. In contrast to the GL and GL-LED, the KM CL-70f has light measuring capabilities across the entire visible spectrum within the range of 380 – 780 nm.[16,17] This indicates that the KM CL-70f detects more illuminance than the GL and GL-LED because it has the capabilities of measuring a broader range of light within the visible spectrum.

Quantifying light illuminating an object, surface or general workplace is vital to determine if lighting in an occupational environment complies with regulations and standards.[7] However, in the scope of occupational hygiene, information regarding what specifications an illuminance meter needs to conform to in order to make accurate illuminance measurements in the workplace, are incomplete. Considering the technological development/progress of available lighting used in the workplace, illuminance meters should also advance to accurately measure modern light sources. Occupational hygiene practitioners should be aware of the limitations of the instruments used for measuring illuminance and should apply careful considerations when selecting an illuminance meter for monitoring workplaces. There is a need for the development of regulations and standards to indicate which illuminance meters are best suited for measuring light in the workplace to allow employers to provide a workplace that is free of risks to health and safety while also promoting increased productivity.[1,2]

Limitations of this study include that this study was carried out under strictly controlled laboratory conditions where illuminance meters were placed precisely one metre away from the selected lamp. In workplace settings, lighting positioning, lamp type and required illuminance levels are adjusted to best aid the visual task being carried out. A future study could be conducted where illuminance meter measurements are compared in practical workplace settings where the measurements are taken at different distances from a light source. This will provide greater insight into how illuminance meters compare against one another in monitoring illumination in a practical workplace setting. Furthermore, values obtained using different illuminance meters could be compared against regulations and standards that state minimum values of maintained illuminance for the specified areas and tasks being monitored. Information gathered will indicate whether illuminance values obtained with a certain illuminance meter will correspond with other instruments in terms of compliance/non-compliance to regulations and standards.

3.4 Conclusions

This study compared illuminance values obtained using three illuminance meters and found that in most instances there were statistically significant differences between values obtained. The results indicate that, although spectral wavelength qualities of specific lamp types remained similar when measuring different light output levels, it was found that the degree to which illuminance values differed, increased when measuring lamps with higher outputs. It is concluded that, to achieve accurate measurements of modern lamps, such as CFLs and LEDs, illuminance meters having a spectral response capable of measuring the entire visible spectrum should be used. Furthermore, it can be concluded that due to the differences in spectral wavelength qualities of lamps, illuminance meters should be calibrated to measure modern lamp types such as CFLs and LEDs. Lastly, there is a need for the development of regulations and standards that define which qualities of illuminance meters are required for accurately measuring light within the workplace.

Lessons learned

1. Illuminance values obtained from illuminance meters differ significantly when measuring modern light sources such as CFLs and LEDs.
2. Lamps with a higher light output lead to increased illuminance value differences between illuminance meters.

Supplementary results

Table S1: Descriptive statistics of illuminance levels measured for each lamp type measured using the GL (MIT, South Africa), the GL-LED (MIT, South Africa) and the KM CL-70f (Konica Minolta, Japan)

	Lamp Type	Min	Max	Range	Mean	SD
Goldilux auto-ranging light meter	hICL Low	14.30	23.00	8.70	18.01	3.21
	hICL Med	27.80	34.50	6.70	30.96	2.33
	hICL High	52.80	56.00	3.20	53.83	1.04
	CFL Low	21.50	23.60	2.10	22.68	0.64
	CFL Med	50.60	56.00	5.40	53.31	1.67
	CFL High	106.30	117.40	11.10	111.50	4.21
	LED Low	64.50	68.80	4.30	66.02	1.64
	LED Med	107.80	114.20	6.40	110.10	2.16
	LED High	161.60	169.70	8.10	166.30	2.47
Goldilux LED	hICL Low	14.20	23.50	9.30	18.24	3.40
	hICL Med	28.00	36.70	8.70	32.50	2.74
	hICL High	55.30	58.90	3.60	56.77	1.10
	CFL Low	22.90	24.60	1.70	23.76	0.53
	CFL Med	54.20	61.60	7.40	57.09	2.32
	CFL High	115.20	126.60	11.40	120.10	4.19
	LED Low	69.30	74.30	5.00	71.07	1.83
	LED Med	116.80	123.50	6.70	119.20	2.29
	LED High	175.30	181.90	6.60	179.30	2.33
Konica Minolta CL-70f	hICL Low	16.00	27.00	11.00	19.89	3.56
	hICL Med	31.50	40.40	8.90	35.51	3.49
	hICL High	59.40	64.10	4.70	61.44	1.70
	CFL Low	25.00	26.70	1.70	25.70	0.48
	CFL Med	58.90	66.10	7.20	62.10	2.65
	CFL High	122.00	132.00	10.00	126.70	3.16
	LED Low	73.20	77.60	4.40	74.81	1.65
	LED Med	122.00	129.00	7.00	124.30	2.40
	LED High	184.00	190.00	6.00	187.40	2.19

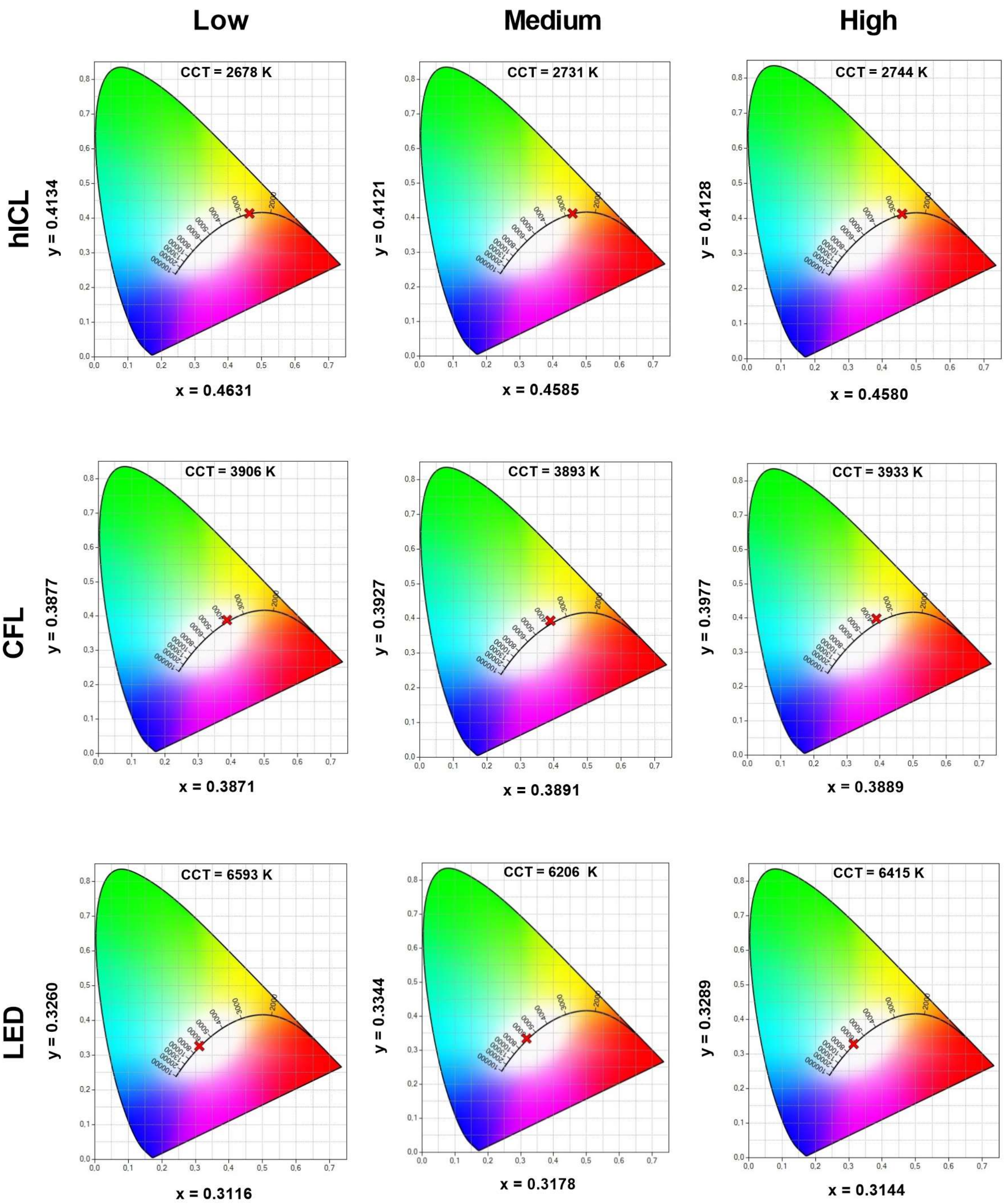

Figure S1: CCT of low-, medium-, and high-output hICLs, CFLs and LEDs, measured using the KM CL-70f (Konica Minolta, Japan).

Reference list

1. Smith NA. Light and Lighting. In: Gardiner K, Harrington JM, editors. Occupational Hygiene. 3rd ed. Malden (Mass): Blackwell; 2005. p. 268-285.

2. Jayawardena A, Duffy D, Manahan JM. Lighting matters in industrial environments: A framework linking workplace safety to lighting quality metrics. IEEE Trans Ind Appl. 2017; 23:54-63.

3. Giannuzzi A, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 6, Halogen and incandescence lamps; [cited 2020 Nov 27]. p. 87-106. Available from: https://link.springer.com/content/pdf/10.1007%2F978-1-4471-6633-7.pdf.

4. Cole M, Driscoll T. The lighting revolution: If we were experts before, we're novices now. IEEE Trans Ind Appl. 2014; 50:1509-1519.

5. Heyes J. Incandescent bulb banned… now what? EE Publishers[Internet]. 2014 Jun 16 [cited 2021 April 21] Available from: https://www.ee.co.za/article/incandescent-bulb-banned-now.html.

6. American Conference of Governmental Industrial Hygienists. TLVs® and BEIs®: Threshold limit values for chemical substances and physical agents & biological exposure indices. 7th ed. 2019. Cincinnati, OH: ACGIH Worldwide; 2019. 239-241 p.

7. Deonarine DC. Occupational hygiene the science. 3rd ed. Bloemfontein (South Africa): Nershco (Pty) Ltd and VDH Industrial Hygiene CC; 2014. Chapter 6.5, Illumination; p. 139-174.

8. South Africa. Occupational Health and Safety Act 85 of 1993 (Act No. 85 of 1993).

9. South African Department of Labour. Machinery and Occupational Safety Act: environmental regulations for workplaces. Government Gazette No. 268(10988), 1983 Oct 16 (published under Government Notice R 2281).

10. Bizjak G. LEDs and measurements – how much light source influence the measurement results. In: Proceedings of the 11th International Conference and Exposition on Electrical and Power Engineering; 2020 Oct 22-23; Lasi, Romania. New York: IEEE; 2020. p. 755-761.

11. The International Commission on Illumination Central Bureau. Characterization of the Performance of Illuminance Meters and Luminance Meters. Vienna: CIE 023/E:2013.

12. Giannini A. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 1, Radiometric and photometric quantities and laws; [cited 2021 Mar 30]. p. 1-22. Available from: https://link.springer.com/content/pdf/10.1007%2F978-1-4471-6633-7.pdf.

13. Bergen T. Photometry of lighting devices. Light Eng. 2017; 25:80-85.

14. The International Commission on Illumination Central Bureau. International Organization for Standardization. Photometry – the CIE system of physical photometry. ISO 23539-2005.

15. American Medical Association. Human and environmental effects of light emitting diode (LED) community lighting [Internet]. The Council on Science and Public Health; 2016 [cited 2021 Jul 27] Available from: https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/AMA_Report_2016_60.pdf.

16. Marmit. Goldilux. https://www.marmit.co.za/wp-content/uploads/2018/02/Autoranging-Light-Meter.pdf (accessed 23 Mar 2020).

17. Konica Minolta Sensing Americas. CL-70F CRI Illuminance Meter, Konica Minolta sensing. https://sensing.konicaminolta.us/products/cl-70f-cri-illuminance-meter/ (accessed 28 Feb 2020).

18. Illuminating Engineering Society Testing Procedures Committee. IES guide to lamp seasoning. JIES. 1989; 18:150-152.

19. International Electrotechnical Commission. Photobiological safety of lamps and lamp systems. Brussels: EN 62471-2008.

20. The South African Bureau of Standards. South African National Standards. Self-ballasted lamps for general lighting services — Performance requirements. SANS 60969:2010.

21. The South African Bureau of Standards. South African National Standards. Interior lighting, Part 1: Artificial lighting of interiors. SANS 10114-1:2005.

22. Illuminating Engineering Society Testing Procedures Committee. Electrical and photometric measurements of solid-state lighting products. New York, NY. IES LM-79-08:2008.

23. Ellison SLR. Analysis of variance. In: Barwick VJ, Duguid TJ, editors. Practical statistics for the analytical scientist: A bench guide [Internet]. Cambridge: RSC Publishing; 2009 [cited 2019 Jul 16]. Chapter 6. Available from: https://eds-a-ebscohost-com.nwulib.nwu.ac.za/eds/detail/detail?vid=4&sid=586193c8-d6a8-44a3-bf39-a8eab53d5061%40sdc-v-sessmgr03&bdata=JnNpdGU9ZWRzLWxpdmU%3d#AN=519294&db=nlebk.

24. Fontani D, Francini F, Sansoni P. Sustainable indoor lighting [Internet]. 1st ed Cham (Switzerland): Springer; 2015. Chapter 10, Building Glasses and Skylights: Optical Characterization; [cited 2020 Nov 29]. p. 167-193. Available from: https://link.springer.com/chapter/10.1007%2F978-1-4471-6633-7_3.

25. van Bommel W. Incandescent replacement lamps and health. Light Eng. 2011; 19:8-14.

26. Ouellette M. Photometric errors with compact fluorescent sources. IEEE Trans Ind Appl. 1992; 2:1865-1867.

Chapter 4: Concluding chapter

This concluding chapter is divided into four sections, namely main findings, recommendations, a limitation, and future studies. The aims, objectives and hypotheses as stated in Chapter 1 are referred to and addressed. Recommendations on the suitability of illuminance meters for certain scenarios are made and a limitation followed by recommended future studies are discussed. Final remarks involving the need for standardisation and regulations regarding the selection of illuminance meters conclude this chapter.

4 Main findings

The aim of this study was to measure and compare illuminance values obtained under laboratory conditions with the Goldilux auto-ranging light meter (GL), Goldilux-LED auto-ranging light meter (GL-LED) and the Konica Minolta CL-70f (KM CL-70f) illuminance meter. This was realised by measuring low-, medium- and high-output lamps. Lamps measured included 2900 K halogen incandescent lamps (hICLs), 4000 K compact fluorescent lamps (CFLs) and 6500 K light emitting diodes (LEDs). Illuminance was measured precisely one metre away from the lamp using the three above mentioned illuminance meters. Once illuminance measurements were obtained, a one-way analysis of variance (ANOVA) test, followed by Tukey's multiple comparisons post hoc test, was used to determine if there were any significant differences between illuminance levels of the different lamp types as measured by the various illuminance meters.

In most instances, results indicated that there were highly significant differences in the measurements obtained from different lamp types. It was observed that, in all cases, the KM CL-70f measured the highest illuminance values, followed by the GL-LED and the lowest values were observed with the GL. The most significant differences were observed when measuring LEDs, followed by CFLs and the least significant differences between illuminance meters were observed when measuring hICLs (Objective 1). When comparing the illuminance levels measured from low-, medium- and high-output hICLs, CFLs and LEDs, it was found that there were no statistically significant differences between illuminance meters when measuring low-output ICLs. No significant differences were observed between the GL and GL-LED, and the GL-LED and KM CL-70f when measuring medium-output ICLs. However, when measuring high-output ICLs, low-, medium- and high-output CFLs and LEDs, it was found that the degree in which illuminance values differed significantly, increased when measuring higher outputs (Objective 2). Spectral wavelength measurements confirmed that hICLs have a similar wavelength distribution as the traditional unpolarised ICL used to calibrate illuminance meters.

However, CFLs and LEDs have an entirely different spectral wavelength distribution in comparison to hICLs and ICLs.[1]

Colour correlated temperature (CCT) measurements obtained using the KM CL-70f indicate that there were slight differences between measured CCTs and rated manufacturer specifications. Differences in CCT ranged between 169-245 K for hICLs, 81-142 K for CFLs and 15-360 K for LEDs. This is possibly due to the differences in standard conditions used in this study in comparison to the standard conditions lamps are manufactured and tested under by the manufacturer (Objective 3).

In Chapter 1, it was hypothesised that, due to illuminance meters being calibrated using an unpolarised ICL with a CCT of 2856 K, and hICLs have similar CCTs and spectral qualities as the traditional ICL, no statistically significant differences exist between the three illuminance meters when measuring illuminance from hICLs (Hypothesis 1).[2] There were no statistically significant differences between illuminance values when measuring low-output hICLs and there were no statistically significant differences between illuminance values obtained by medium-output hICLs between the GL and GL-LED and between the GL-LED and KM CL-70f. There were, however, statistically significant differences between the three illuminance meters when measuring high-output hICLs. Therefore, Hypothesis 1 is only partially accepted.

Secondly, it was hypothesised that the GL (MIT, South Africa) and GL-LED (MIT, South Africa) measure statistically significant lower illuminance values from CFLs when compared to the KM CL-70f (Konica Minolta, Japan) (Hypothesis 2). It was also hypothesised that the GL (MIT, South Africa) and GL-LED (MIT, South Africa) measure statistically significant lower illuminance values from LEDs when compared to the KM CL-70f (Konica Minolta, Japan) (Hypothesis 3). In this study, the GL and GL-LED measured statistically significant lower illuminance values than the KM CL-70f when measuring CFLs and LEDs, therefore, Hypotheses 2 and 3 are accepted.

4.1 Recommendations

Recommendation 1: Quantifying light illuminating an object, surface or general workplace is vital to determine if lighting in an occupational environment complies with regulations and standards.[3] However, in the scope of occupational hygiene, information regarding what specifications an illuminance meter needs to conform to in order to make accurate illuminance measurements in the workplace, are incomplete. Considering the progress of development in technology of available lighting used in the workplace today, illuminance meters should also advance to accurately measure modern light sources. Occupational hygiene practitioners should be aware of the limitations of the instruments used for measuring illuminance and should apply careful considerations when selecting an illuminance meter for monitoring workplaces. Currently, SANS 10114-1 states that illuminance meters should be cosine and colour corrected, however, there are no recommendations considering minimum required quality indices such as the spectral distribution qualities or spectral mismatch factor.[4] There is a need for the development of South African legislation and standards to indicate which qualities illuminance meters should conform to when measuring light in the workplace. This development is essential to allow employers to provide a workplace that is free of risks to health and safety while also promoting increased productivity.[5,6] In this study, the KM CL-70f measured significantly higher illuminance values in comparison to the GL and GL-LED due to the KM CL-70f having a spectral response that measures the entire visible spectrum.[9,10] It is therefore, recommended that illuminance meters that are capable of measuring the entire visible spectrum, such as the KM CL-70f, be used to measure light sources in workplaces.

Recommendation 2: Currently LEDs and CFL lamps dominate the lighting market and are used in most homes and industrial workplaces, thus rendering the traditional ICL outdated.[7] However, despite ICLs being banned from being manufactured and imported in 2015 in South Africa, illuminance meters are still calibrated using light from a standard unpolarised incandescent lamp with a CCT of 2856 K.[1,7] The AMA (2016) and Bergen (2017) state that modern lamps, such as LEDs and CFLs, have entirely different spectral properties in comparison to the previously popular ICL.[1,8] Due to this, it is recommended that illuminance meters such as the GL-LED and KM CL-70f should be used to monitor workplaces that use modern light sources or illuminance meters should be calibrated using CFLs or LEDs in order to obtain accurate measurements.

Recommendation 3: The South African National Standard 10114-1 states that, although the quantity of illuminance on specific tasks is important, other factors that contribute to the quality of light should also be considered.[4] Appropriate colour rendering of surfaces and objects has the benefit of increasing productivity by improving recognition of fine details in tasks and visual efficiency. In the occupational setting, precise and constant colour rendering of lighting is important for work performance, for instance, cotton grading and colour matching of paints need specially designed lighting for intricate colour judgements and comparisons. SANS 10114-1 also recommends minimum colour rendering index (CRI) requirements for certain tasks and areas within a workplace. However, basic illuminance meters cannot quantify quality criteria of light, such as CRI and CCTs.[4] It is, therefore, recommended that in these instances, illuminance meters such as the KM CL-70f having the specifications to quantify CRI and CCT, should be used to ensure that the workplace environments conform to quality indices set out in standards.

4.2 Limitation

A limitation found by this study is that this experiment was carried out under strictly controlled laboratory conditions where illuminance meters were placed precisely one metre away from the selected lamp. In workplace settings lighting positioning, lamp type and required illuminance levels are adjusted to best aid the visual task being carried out.

4.3 Future studies

A future study could be conducted where illuminance meter measurements in workplace settings are compared, where the measurements are taken at different distances from a light source. This will provide more insight into how illuminance meters compare against one another when monitored in a workplace setting. Furthermore, values obtained using different illuminance meters could be compared against regulations and standards that state minimum values of maintained illuminance for specified areas and tasks. Information gathered will indicate whether illuminance values obtained by using a certain illuminance meter will correspond to other instruments in terms of compliance/non-compliance to regulations and standards.

Secondly, in this study illuminance meters such as the GL auto ranging light meter and GL LED light meter have lower spectral range capabilities than the KM CL-70f. The GL auto ranging light meter and the GL LED light meter have a spectral range of 410 – 680 nm and the KM CL-70f has a spectral range of 380 – 780 nm.[11,12] This difference means that not all light within the visible spectrum can be measured by the GL and GL-LED. The CIE states that if the spectral responsivity of an illuminance meter and the relative spectral distribution of a light source are known, then spectral mismatch correction factors can be calculated and applied to adjust illuminance measurements. With the use of specialised equipment that determines the relative spectral distribution of light, a future study could include a comparison of the illuminance values obtained from illuminance meters after applying spectral mismatch correction factors.[2]

Thirdly, it is noted that operating illuminance meters where the ambient temperature of the surrounding environment differs from the temperature used when calibrating the instrument, may cause reduced accuracy in meter readings.[2] A future study could be conducted investigating the effects, and to what degree, ambient temperature changes have on illuminance meter readings.

Lastly, the GL auto ranging light meter and the KM CL-70f illuminance meter were calibrated using an unpolarised ICL with a CCT of 2785 K and the GL LED light meter was calibrated against an ISO 17025 compliant GL Master LED light meter (MIT, South Africa) using a stabilised 4000 K LED lamp.[11,12] A future study that includes calibrating the illuminance meters to the specific CCT of the various lamps being measured and comparing results obtained by each illuminance meter, could be conducted to investigate if the impact of calibration conditions on the illuminance measurement results.

References

1. Bergen T. Photometry of lighting devices. Light Eng. 2017; 25:80-85.

2. The International Commission on Illumination Central Bureau. Characterization of the Performance of Illuminance Meters and Luminance Meters. Vienna: CIE 023/E:2013.

3. Deonarine DC. Occupational hygiene the science. 3rd ed. Bloemfontein (South Africa): Nershco (Pty) Ltd and VDH Industrial Hygiene CC; 2014. Chapter 6.5, Illumination; p. 139-174.

4. The South African Bureau of Standards. South African National Standards. Interior lighting, Part 1: Artificial lighting of interiors. SANS 10114-1:2005.

5. Jayawardena A, Duffy D, Manahan JM. Lighting matters in industrial environments: A framework linking workplace safety to lighting quality metrics. IEEE Trans Ind Appl. 2017; 23:54-63.

6. Smith NA. Light and Lighting. In: Gardiner K, Harrington JM, editors. Occupational Hygiene. 3rd ed. Malden (Mass): Blackwell; 2005. p. 268-285.

7. Bizjak G. LEDs and measurements – how much light source influence the measurement results. In: Proceedings of the 11th International Conference and Exposition on Electrical and Power Engineering; 2020 Oct 22-23; Lasi, Romania. New York: IEEE; 2020. p. 755-761.

8. American Medical Association. Human and environmental effects of light emitting diode (LED) community lighting [Internet]. The Council on Science and Public Health; 2016 [cited 2021 Jul 27] Available from: https://www.darksky.org/wp-content/uploads/bsk-pdf-manager/AMA_Report_2016_60.pdf.

9. Bisi O. Visible and invisible – the wonders of light phenomena [Internet]. 3rd ed. Cham (Switzerland): Springer; 2015. Chapter 2, Experiments with light; [cited 2020 Feb 17]; p. 49-99. Available from https://link-springer-com.nwulib.nwu.ac.za/content/pdf/10.1007%2F978-3-319-09825-8.pdf.

10. Wiltshire LC. Light. In: Coaton JR, Marsden AM, editors. Lamps and lighting [Internet]. New York (NY): Routledge; 1996 [cited 2020 Sep 16]. Chapter 1. Available from: https://ebookcentral-proquest-com.nwulib.nwu.ac.za/lib/northwu-ebooks/detail.action?docID=1016145.

11. Marmit. Goldilux. https://www.marmit.co.za/wp-content/uploads/2018/02/Autoranging-Light-Meter.pdf (accessed 23 Mar 2020).

12. Konica Minolta Sensing Americas. CL-70F CRI Illuminance Meter, Konica Minolta sensing. https://sensing.konicaminolta.us/products/cl-70f-cri-illuminance-meter/ (accessed 28 Feb 2020).

Annexure A

WOORDE WAT WERK
WORKING WORDS

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22 November 2021

LANGUAGE EDITING STATEMENT

I, Jannetjie Levina De Kock hereby declare that the thesis

A comparison of illuminance values obtained from three illuminance measuring instruments

by C I Holleran

for submission to the NWU
in the Niche area Occupational Hygiene and Health Research Initiative (OHHRI)

- has been edited for language correctness and spelling.
- has been edited for consistency (repetition, long sentences, logical flow)

No changes have been made to the document's substance and structure (nature of academic content and argument in the discipline, chapter and section structure and headings, order and balance of content, referencing style and quality).

J L DE KOCK

Annexure B

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North-West University Health Research Ethics Committee (NWU-HREC)

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26 August 2020

RESEARCH ETHICS COMMITTEE LETTER OF DECISION: NO RISK

Based on the review by the North-West University Health Research Ethics Committee (NWU-HREC) on 26/08/2020, the NWU-HREC hereby clears your study as a no risk study. This implies that the NWU-HREC grants its permission that, provided the general conditions specified below are met, the study may be initiated, using the ethics number below.

Study title: A comparison of illumination values obtained from three illuminance measuring instruments
Principal Investigator/Study Supervisor/Researcher: CJ van der Merwe
Student: CI Holleran - 25122444

Ethics number: N W U - 0 0 4 4 4 - 2 0 - A 1

Institution	Study Number	Year	Status
NWU	00444	20	A1

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application Type: Single study
Commencement date: 26/08/2020

Risk: No Risk

General conditions:

The following general terms and conditions will apply:

- *The commencement date indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-HREC reserves the right to:*
  - *request access to any information or data at any time during the course or after completion of the study;*
  - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research;*
  - *withdraw or postpone clearance if:*
    - *any unethical principles or practices of the study are revealed or suspected;*
    - *it becomes apparent that any relevant information was withheld from the NWU-HREC or that information has been false or misrepresented;*
    - *submission of the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or*
    - *new institutional rules, national legislation or international conventions deem it necessary.*
- *NWU-HREC can be contacted for further information via Ethics-HRECApply@nwu.ac.za or 018 299 1206*

Special conditions of the research approval due to the COVID-19 pandemic:

Please note: Due to the nature of the study i.e. (laboratory work comparing the illumination values with three different illumination measuring instruments), this study will be able to proceed during the current alert level, following receipt of the approval letter. No additional COVID-19 restrictions have been placed on the study except that the researcher must ensure that before proceeding with the study that all research team members have reviewed the North-West University COVID-19 Occupational Health and Safety Standard Operating Procedure.

The NWU-HREC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-HREC for any further enquiries or requests for assistance.

Yours sincerely,

Digitally signed by Prof Petra Bester
Date: 2020.08.26 08:20:47 +02'00'

NWU-HREC Chairperson

Digitally signed by Wayne Towers
Date: 2020.08.25 22:02:18 +02'00'

Head of the Faculty of Health Sciences Ethics Office for Research, Training and Support

Current details: (13210672) G:\My Drive\My Documents 20190227\NWU-HREC\NWU-HREC_Approval Letters\9.1.5.4.3_LOD_NWU-00000-20-A1_2020mmdd.docm
13 February 2020

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