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Human responses to lighting based on LED lighting solutions

Commissioned by the Chartered Institution of Building Services Engineers and the Society of Light and Lighting

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Human Responses to Lighting based on LED Lighting Solutions

Commissioned by the Chartered Institution of Building Services Engineers and the Society of Light and Lighting

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Abstract

LED technology is advancing rapidly and LEDs are being used for lighting in an increasingly wide variety of situations. Energy efficiency data are favourable, but there is a lack of data relating to the effects on health and lighting quality of the current generation of LED lighting solutions. This report seeks to directly address the areas where data are lacking based on up to date knowledge of human responses to light, and international exposure guidelines, applied to measurements taken of a range of LED lighting products currently on sale to the public, businesses and commissioners of outdoor lighting projects in the UK.

This study was commissioned and funded by Chartered Institution of Building Services Engineers and the Society of Light and Lighting.

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Executive Summary

This report concerns Human responses to lighting based on LED lighting solutions and has been produced by Public Health England, PHE, for the Chartered Institution of Building Services Engineers, CIBSE, and the specialist professional body for lighting, the Society of Light and Lighting, SLL.

A range of LED luminaires was tested, which is subdivided into three main categories:

Table 1: LED lighting applications

Application	Description
Domestic use (or home use)	LED replacements for light bulbs, spots and other energy efficient light bulbs
Office and commercial use	LED panels, from smaller wall panels up to 600 mm square ceiling panels
Street lighting	Overhead LED lighting typically used for roads and public areas

The health hazards and the positive impacts from lighting are not exclusive to LEDs, or even to artificial light. LEDs are just one of many technologies used to create artificial light. The importance of LEDs lies in their potential to provide increasingly ergonomically efficient lighting for many applications. The current definition of energy efficiency used in lighting is based on luminous flux. This definition does not always reflect the cost of producing the desired human responses, because it concentrates on only one of a range of effects of lighting on the human body, namely brightness.

It is also hard for energy efficiency measures to capture negative impacts or the changes in the demands on lighting over 24 hours. With a wide choice of lighting technologies, the appropriate measures, including energy efficiency measures, should be selected when deciding which solution and lighting technology is appropriate for any given situation. Inevitably, a balance must be struck between energy efficiency and competing factors.

The aim is to describe the light output measured with respect to the main human responses to light as currently understood. The analysis is divided into three packages or work packages:

Table 2: Work package descriptions

Package	Scope
Colour	The colour, colour rendering and illuminance of a range of fixed brightness and dimmable LEDs
Flicker	The variation in illuminance at high frequencies of a range of fixed brightness and dimmable LEDs
Spectrum	The potential for LED street lighting at night to cause unwanted disruption to healthy circadian rhythms AND The ocular safety of all LED types measured against international exposure guidelines

Contents

1 Introduction

Light emitting diodes (LEDs) are being promoted for a wide range of lighting applications on the basis of increased energy efficiency compared with some other technologies. However, lighting quality and its positive or negative impact on human health are also important. This report presents the results of a study of a varied purposive sample of over 100 LED lamps and luminaires for domestic, office and street lighting. Up to 3 lamps from each model were tested. Altogether there were 38 distinct LED models and 8 models of non-LED domestic lighting for comparison.

The requested work was subdivided into three work packages summarised in Table 2 and explained below: Colour, Flicker and Spectrum.

1.1 Colour

The colour package relates to *the colour, colour rendering and illuminance of a range of fixed brightness and dimmable LEDs* (see Table 2 on page iii).

The two most widely used metrics of light are illuminance, E_V, and correlated colour temperature T_{CP}, broadly speaking describing the amount and colorimetric blueness of lighting. The quality of lighting has been measured using the International Commission on Illumination (CIE) General CRI (Color Rendering Index), R_a. Due to the selection process of its test colours, the CRI system represents a subjective solution to the colour rendering problem as it relates to incandescent and fluorescent lighting.

The opportunity with LEDs to manipulate spectral power distributions, whilst maintaining colour (or blueness), means that LEDs are often unfairly promoted or penalised by this scale. Colour rendering phenomena have meant that it has never been possible to evaluate colour appearance under lighting without considering spectrum, but the consequence of LED technology in particular is that colour aspects of lighting are now more immediately linked with the finer resolution of spectra than ever before.

This report considers the range of colour metrics and how well they represent an observer's experience of LEDs.

1.2 Flicker

The flicker package relates to *the variation in illuminance at high frequencies of a range of fixed brightness and dimmable LEDs* (see Table 2 on page iii).

Flicker may occur because the output of a source is changing with time, or because of movement of the source or the observer. Not everyone has the same sensitivity to flicker and this presents challenges for unambiguous assessments. Traditionally, flicker has only been considered in the frequency range that can be observed (up to about 80 Hz). However, some people are sensitive to flicker at higher frequencies and possibly up to 1 kHz without there being any visual sensation of the flicker. The visual system of the eye does provide a natural filter for high frequencies and this is discussed later.

Most sources operating from a 50 Hz mains supply will have a degree of flicker, but the magnitude will be dependent on several factors. For example, an incandescent lamp will flicker at 100 Hz, but due to the thermal inertia of the hot filament, this will manifest as a ripple on the emitted optical radiation. With LEDs it is possible to modulate the drive current to the emitter and the optical radiation emitted may follow that drive current with very little lag.

Methods used to dim some light sources may involve modulating the drive current and therefore convert a source that does not flicker without the dimmer into one that does.

1.3 Spectrum

The spectrum package relates to risk versus benefit of human exposure to optical radiation. The package is restricted to considering *the potential for LED street lighting at night to cause unwanted disruption to healthy circadian rhythms AND the ocular safety of all LED types measured against international exposure guidelines* (see Table 2 on page iii).

Humans originally evolved under optical radiation from the sun. Whether the exposure is to ultraviolet radiation, visible radiation (light) or infrared radiation, there is generally an optimum level of exposure to the eye and/or the skin that provides maximum benefit (Figure 1). It should be noted that there are no scales on the Figure: these depend on a range of factors, as described below.

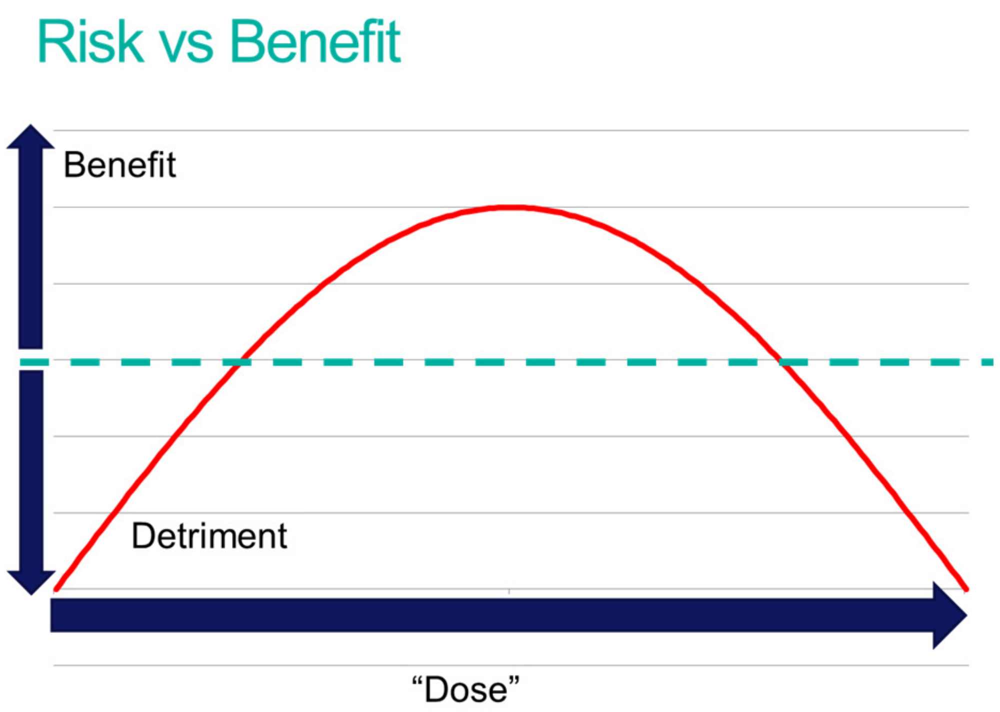


Figure 1: Risk vs Benefit curve for human exposure to optical radiation

For ultraviolet radiation, too much exposure is likely to trigger sunburn or photokeratitis in the short-term and possibly cancer (of the eye or skin) in the long term. However, too little ultraviolet radiation impacts on vitamin D status, which has implications for bone health. Light is needed to be able to see, to entrain the circadian rhythm and has an alerting effect. Too much light can cause dazzle, glare and afterimages and, at higher levels of exposure, eye or skin injuries. However, there are times when the greatest benefit is from no light at all, for example when trying to get to sleep. Therefore, knowledge of the activity being carried out may be relevant. Insufficient exposure to infrared radiation, for completeness, may mean that we get cold, whilst too much may cause over-heating or burns.

Metrics for both harm and benefit require knowledge of the spectrum and exposure profile of optical radiation received by the person.

1.3.1 Harm

The International Commission on Non-ionizing Radiation Protection publishes guidelines on exposure limits for human exposure to optical radiation (ICNIRP, 2004 and 2013). These guidelines are quite mature and represent levels below which harm is very unlikely to occur in most of the population.

The Control of Artificial Optical Radiation at Work Regulations 2010 refers to exposure limit values in the Artificial Optical Radiation Directive of 2006 (EC, 2006). These exposure limits are based on the ICNIRP guidelines, but for visible and infrared radiation refer to a 1997 edition. The Regulations require an assessment to determine if people at work who are exposed to artificial optical radiation (including from light sources) are likely to exceed the exposure limit values. This assessment can be theoretical if appropriate data are available. If those at work are likely to exceed the exposure limits then measures need to be put into place to ensure that those workers are not at risk.

When considering personal exposures, the Regulations also require the employer to take account of workers who may be particularly photosensitive. However, this only needs to be done if a worker reports that they are particularly photosensitive or if symptoms arise following exposure to the source of optical radiation. There is no need for an employer to carry out this specific assessment just in case an employee may be photosensitive. Whilst this requirement applies only to employers and does not extend to persons who are not at work, there are many situations in which a more general duty of care may apply.

When considering the exposure of an individual for comparison with the exposure limits, it is important to consider what is reasonable. For example, unless there was a specific application that required a worker to do so, intentional staring at optical radiation sources other than screens or indicator lights would not be considered normal behaviour. It is also important to recognise that the Regulations do not apply to people who are not workers (at that time). However, the ICNIRP guidelines could be used as good practice for compliance with more general health and safety legislation, such as the Health and Safety at Work etc. Act 1974 and Regulations made under that Act, such as the Management of Health and Safety at Work Regulations 1999.

The ICNIRP guidelines consider primarily two types of limits: those that have a maximum value accumulated over a period of time, for example during a working day; and those that have a peak instantaneous level that should not be exceeded. The former applies to the ultraviolet limits and the blue light hazard and is termed “time-weighted averaging”, whereas the latter applies to thermal hazards, often from intense short pulses. Time-weighted averaging is an important concept because it can be used to take account of real exposure scenarios during a day. For example, someone may get very close to a source, but only for a short time, and then spend longer times at some distance from the source.

Although exposure to light may not cause direct harm to the eye or the skin, it can still compromise a person's ability to carry out certain activities. For example a high luminance source in an observer's field of view may be a source of glare, which could be annoying or compromise vision. Light incident on the eye may also cause distraction, glare and afterimages with the impact on the individual being dependent on the activity they are trying to carry out, the ambient light level (coupled with the degree of light adaptation) and age. In general for illumination sources, these effects occur at exposure levels much lower than the ICNIRP guideline levels for harm.

1.3.2 Benefit

The metrics for determining the beneficial effects of exposure to optical radiation are not as well defined as those for harm. The beneficial effects are also likely to be dependent on personal factors, such as the task being undertaken, time of day, prior light exposure history and age. Minimising light at night is appropriate for most people to assist with good quality sleep, although some people feel more comfortable with a low level of light at night. Light during the day is needed to allow people to go about their daily lives and is important for circadian rhythm entrainment. However, the specific optical radiation stimuli required and how that interacts with exposure profile (timing) are still open to scientific debate.

The spectral luminous efficiency function, $V(\lambda)$, provides a reasonable indicator for the visual response of the eye to different wavelengths, but it does not directly account for requirements of the individual carrying out specific tasks. Lucas *et al* (2014) proposed that spectral measurements should be carried out in order to determine the impact of the optical radiation on the five retinal sensors (three types of cones, the rods and the intrinsically photosensitive retinal ganglion cells). It is important that any pre-receptoral filtration (particularly as the lens changes with age) is taken into account. Using this approach, it is possible to compare different spectra to determine the impact on a number of beneficial effects of light through the eye pathway.

1.3.3 Effects on other species

This report concentrates on the impact of the optical radiation from LEDs on human health. It does not specifically cover the impact on flora and fauna. However, it is recognised that most living systems benefit from a 24 hour light/dark cycle.

The report does not specifically address issues relating to impact of LED lighting on dark skies and light pollution. However, some of the findings will be relevant to the discussions in these areas.

2 Types of lamps and measurements

A varied purposive sample of domestic lighting, office lighting and street lights were selected:

a 92 domestic LED lamps, 24 different models plus 8 models of non-LED lamps

b 20 office LED panels, 8 models

c 16 LED street lights, 6 models

Domestic-class LEDs were purchased from a range of retailers and manufacturers:

a 13 B22 bayonet models (around 450 or 600 lumens)

b 9 GU10 spots (around 350 lumens)

c 2 models with alternative screw fittings (E14 and E27)

Eight further models were added for comparison in the domestic class:

a 2 B22 compact fluorescent lamps (CFL)

b 2 B22 incandescent light bulbs (Inc)

c 4 tungsten-halogen models (TH), including 2 B22 light bulbs and 2 GU10 spots

Most office-class LEDs were purchased. Three loan models (with electronic drivers) were supplied by contacts through CIBSE and SLL in exchange for measurement results:

a 4 600 mm by 600 mm ceiling tile panels (including the three loan models)

b 2 small square panels

c 2 small circular panels

All six LED street light model (with built-in electronic drivers) were loans provided in exchange for measurement results. Whilst not identical, their luminaire styles appeared quite similar.

Figure 2: A selection of the LED lamps and luminaires. Clockwise from top-left B22 pearl, B22 filament, small panel (circular), small panel, GU10 Fresnel and microlens, GU10 multichip

2.1 Design

A breakdown of the design of the lamp models by "type", "class", "style" and fitting is set out below in Table 3. The results relate to LEDs or non-LEDs of one class at a time, so the results for domestic, office and street-class lighting can be seen separately in Sections 6, 7 and 8 respectively.

All the LED lamps considered comprised a blue LED emitter with a yellow phosphor, referred to as "white LEDs" in this report, as these make up the majority of current LED solutions for lighting. Some dimmable lamps were included in the sample, as well as some lamps advertised with a range of correlated colour temperature (CCT, see Section 3).

Table 3: A breakdown of LED and non-LED lamps tested

Type	Class	Style	Fitting	Models
CFL	Domestic	Triple bend	B22	1
CFL	Domestic	Mini spiral	B22	1
Inc	Domestic	Pearl (pre 2009 phase-out)	B22	1
Inc	Domestic	Filament	B22	1
TH	Domestic	Filament	B22	2
TH	Domestic	Filament	GU10	2
LED	Domestic	Filament	B22	5
LED	Domestic	Light guide	B22	2
LED	Domestic	Light guide	E14	2
LED	Domestic	Pearl	B22	5
LED	Domestic	Multichip and lens	GU10	3
LED	Domestic	Fresnel and microlens	GU10	2
LED	Domestic	Microlens	GU10	3
LED	Domestic	Multichip	GU10	1
LED	Domestic	Multichip corn	B22	1
LED	Office	Small panel	Various	4
LED	Office	600 mm by 600 mm panel	Ceiling tile	4
LED	Street	Multichip, integrated unit	Various	6

2.2 Measurements

2.2.1 Spectral irradiance

The spectral irradiance at 300 mm from each lamp was measured in a darkened, temperature-controlled laboratory at 22°C using high spectral resolution instruments with calibrations for wavelength position, cosine response, and an absolute sensitivity calibration traceable to international standards. Measurement accuracy was estimated at approximately 5%, but for colorimetry and comparisons between different wavelengths or lamps, relative measurements were considerably more accurate.

The raw data were processed to give 1 nm spectral irradiance data for LEDs from 350 nm to 799 nm and for non-LEDs, which may emit below 350 nm, from 250 nm to 799 nm.

The more exacting colorimetry standards and calculations call for 1 nm resolution spectral data from 360 nm to 830 nm (Wyszecki and Stiles, 1982). Supplementary measurements confirmed that the region between 800 nm and 830 nm made negligible differences to the results in this study. In any case, the spectral irradiance of the LEDs was extrapolated up to 830 nm for illuminance and colorimetry calculations.

Table 4: Matrix of optical measurements and other data collected

LED (non-LED)	Domestic	Small panels	600 mm panels		Street lights
Number	92 (23)	12	3	5	16
Models	24 (8)	4	1	3	6
Source	Purchase	Purchase	Purchase	Loan	Loan
			All lamps and packs		
Photographs	✓	✓	✓	✓	✓
Cost, pack information	✓	✓	✓	✗	✗
			All lamps, three per model (see note)		
Spectral power distribution					
Warmed-up	✓	✓	✓	✓	✓
During first warm-up	✓	✓	✗	✗	✗
Other angles	✓	✓	✗	✗	✗
Cross-section	✗	✗	✓	✓	✗
Flicker (modulation)	✓	✓	✓	✓	✓
Power meter	✓	✓	✓	✓	✓

Note
Spectral irradiance, modulation and power meter measurements were taken for at least three lamps per model, where possible, and also for at least one lamp per dimmable model, over the full range of dimming.

2.2.2 Measurement positions for spectral irradiance

Table 4 summarises all the measurement data and other data collected.

Spectral irradiance measurements directly in front of the lamps were taken at the start and end of the measurements in other configurations. The first was taken at least 2 minutes after turning on the lamp. The second was used for all the colour results.

For domestic lamps, the measurements were made 300 mm directly in front of the lamp, and additional measurements were taken at 30° and 60° for BC22, E14 and E27 lamps and at 20° and 30° for GU10 lamps.

For office-class small panels, measurements were made 300 mm directly in front of the lamp, and the additional measurements were taken at 30° and 60°. For large panels, the spectral irradiance measurements were taken in the parallel plane 2 m from the panel face, with the additional measurements taken at lateral offsets of −100 mm and from +100 mm to +1000 mm, with no changes in angle of either the lamp or instrument input optics.

For street lights, a single spectral irradiance measurement was recorded once the lamp had warmed up in the parallel plane 2 m from the luminaire face. Real-time measurement data were used to confirm that the light output had stabilised.

2.2.3 Modulation

After warm-up, the modulation profiles of models from all lamp classes were measured with a 30 kHz sampling frequency, for one second, by placing a photovoltaic detector adjacent to the lamp surface. After subtracting the residual dark signal, the detector response is proportional to the instantaneous illuminance. Flicker frequency, Percent flicker and Flicker index were all calculated from the acquired data (CIE, 2011 - see http://eilv.cie.co.at).

2.2.4 Dimming and power

Nine domestic-class lamp models and all four office-class small panels were described as dimmable on the packaging. For these, spectral irradiance, flicker and power meter measurements were taken with the lamp when connected to a basic rheostat dimmer, described as being LED compatible.

The dimming settings used included maximum (100%) and approximately 70%, 50%, 30%, 10% and at minimum non-zero output, using the peak spectral irradiance as a rough guide. The true illuminance ratio to 100% was calculated afterwards and used to analyse the power consumption data with respect to their relative energy efficiency.

Power meter measurements were taken corresponding to the main measurements of spectral irradiance and during dimming. Both the power meter and dimmer switch were inexpensive consumer items that were purchased directly online.

3 Colour package

This package covers spectral irradiance measurements and the analysis relating to the resulting visible qualities of the lighting, including illuminance, colour temperature and tint, colour rendering, warm-up and batch variations.

Sections 3-5 set out the tests applied to the lamp measurements, including examples, usually drawn from the LED sample. The results are presented in Sections 6-8, separately for domestic, office and outdoor classes of lighting.

3.1 Spectral irradiance and illuminance

Figure 3 shows the typical spectral irradiance distributions of three "white LEDs". A peak in the blue region, from a single colour LED emitting at around 440 nm to 460 nm, is partly converted by a phosphor to provide broad yellow-orange emission at longer wavelengths, around 500 nm to 700 nm. The spectral irradiance is lower in between these two regions, from around 460 nm to 500 nm. The overall spectrum balances the inputs to the three cone types in the human retina, so that white coloured light is created.

If the phosphor dominates, the CCT is lower (see Section 3.2 below), and the colour is a yellowish or "warm" white. If the blue peak dominates, the CCT is higher and a "cooler" blueish colour results. The set of lamps shown in Figure 3 are domestic multichip and lens GU10 LED spots from the same manufacturer with a range of CCT values. Spectral differences, including differences in CCT, affect the efficiency and light quality, as well as the colour.

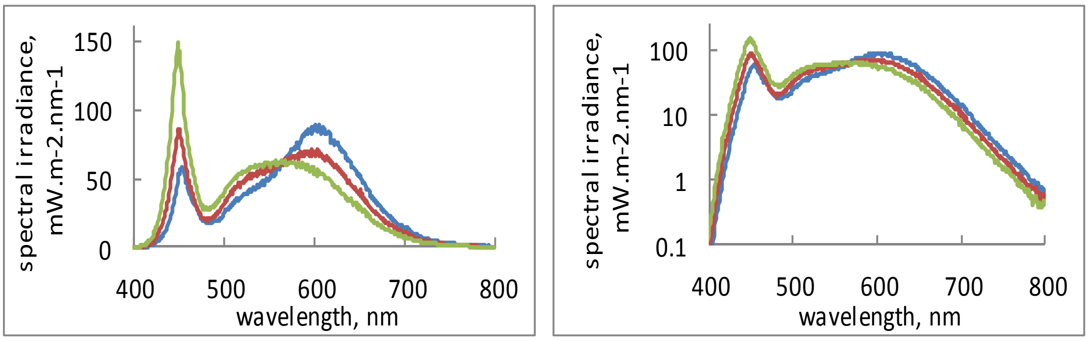


Figure 3: Spectral irradiance at 300 mm for multichip and lens GU10s with a range of CCT values (6520 K green, 4130 K red and 3010 K blue). The graph on the right uses a semi-logarithmic scale.

These are not the only spectral power distributions available with LED lighting. For example, it is also possible to combine different colour LED peaks to provide a white coloured light. RGB and four-colour LEDs, and colour tuneable LEDs, use this approach. Colour tuneable LEDs often add one or more phosphors to the mix; by varying the proportions of the different LED channels, they create different overall colours. RGB, four-colour and colour tuneable LEDs were excluded here, and the products tested all had a single, blue, LED peak.

Lamp illuminances at 300 mm were calculated from spectral irradiance measurements. Although illuminance and luminous flux are closely related, these illuminance measurements would not provide a reliable test of the stated lumen output. However, they can be used to study batch variation, warm-up and other dimming variation, which is discussed later.

3.2 Lamp colour

Correlated Colour Temperature (CCT) is a measure of the blueness of any light source (CIE, 2011) that can be applied to artificial lighting as well as to different daylight conditions. It is used for categorising the appearance of lamps, and quickly conveys colour differences arising from differences in the overall spectral distribution.

Daylight has a CCT of around 6000 K to 7000 K on a clear day and around 4000 K to 5000 K on a cloudy day. Lamps with a CCT below approximately 3500 K have a warmer tint than daylight. Above 3500 K lamps have a noticeably cooler tint. A CCT of around 2700 K is very typical for domestic lighting, although some people prefer higher CCT lighting.

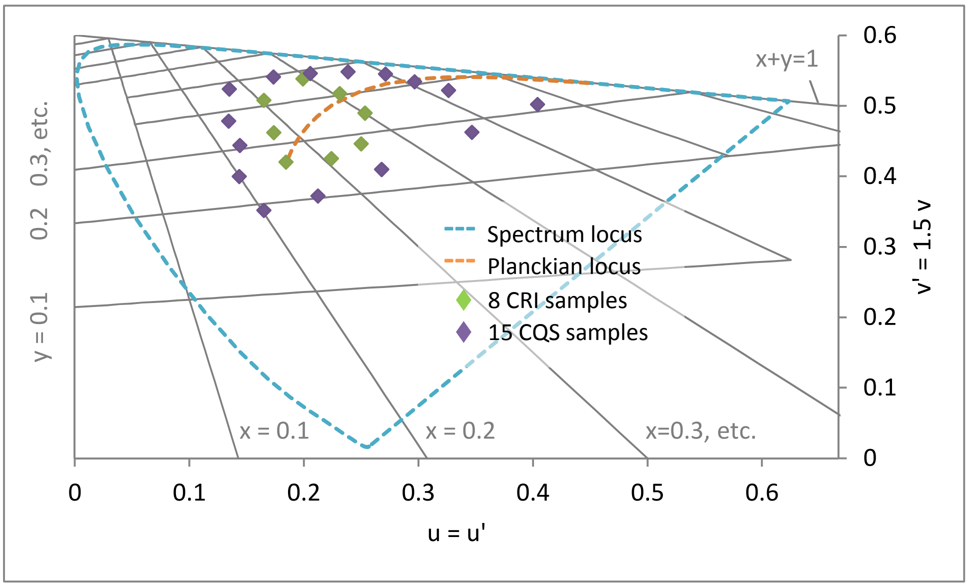


Figure 4: The CIE 1960 uniform colour space diagram (u, v) used for calculating CCT, with mapping of the CIE 1931 colour space (x, y) in grey and (u', v') scale markings. Lamps with higher CCTs appear closer to the left end of the Planckian locus (dotted orange line).

Two lamps with the same CCT may still have colour differences, i.e. other than blue or yellow tints. One measure of this is called Duv (sometimes written Δuv), another measure of distance in colour space from neutrality (i.e. the distance in Figure 4 from the Planckian locus). Duv and CCT values are independent and together they specify an exact colour. Lamps with large positive Duv values have a greenish tint, large negative Duv values a purplish tint.

Large Duv values (i.e. greenish or purplish tints) are usually not considered desirable. This is different to CCT, where different values may be preferred by different people or for lighting used for different purposes. For a light source to have a recognised CCT value, the allowed Duv range given by the CIE is from −0.05 to +0.05 and LED lighting is expected to be between −0.006 and +0.006 (ANSI, 2008; Boyce, 2014).

If multiple lamps are installed in one location, the colour of the lamps should be consistent. This means that any replacement lamps should also be of the same colour. This may not be as easy to achieve with LEDs as with incandescent and tungsten-halogen lamps. If this is important to the end user, the CCT and Duv values should be stated sufficiently accurately and adhered to for future replacements. Duv values are hardly ever stated, however.

3.3 Colour quality and colour rendering

Colour measurements simplify the spectral power distribution of a lamp to what can be seen directly, but they can be inadequate for some measures of a lamp's performance. Perhaps surprisingly, direct colour measurements including CCT do not provide enough information to predict the colour quality of light in practical use. For example, the colour of clothes in daylight, or at home, may not match their colour in the shop even if the light in all three situations has the same colour and intensity.

To determine the ability of a light source to preserve expected or desired relationships between object colours, its spectral power distribution has to be measured, and one or more colour rendering factor of some sort calculated from it. For evaluation purposes this report uses the lighting quality fidelity metric CQS Q_a in conjunction with gamut metric TM-30 R_g and spectral richness metric, H_{Sp}, as explained below (in 3.3.1 to 3.3.3). The CRI and TM-30 colour fidelity metrics are also calculated for reference.

3.3.1 Colour Rendering Index and Colour Quality Scale

The Colour Rendering Index (CRI) and the Colour Quality Scale (CQS) provide systems for calculating the quality of lighting (Boyce, 2014; Davis and Ohno, 2010). The CRI metric R_a is an average score based on how well the illuminant renders the first eight colour samples in the CRI system. It is almost exclusively quoted as the main measure of colour rendering despite having been shown to penalise LED against CFL lighting.

Both CRI and CQS systems use a reference lamp with the same CCT as the lamp's own spectral power distribution as a proxy for its ideal colour rendering properties. This is a successful concept that avoids CCT-induced bias in either index. Both metrics consider how the lamp changes the colour reflected off a number of defined coloured surfaces or "samples".

The position in the CIE 1960 uniform colour space of the first eight CRI colour samples and the 15 CQS colour samples are shown in Figure 4 as though the samples were illuminated by an equal energy spectrum. As this spectrum has a relatively high CCT of 5456 K, the position of the samples are all shifted towards the left, and slightly downward by this illuminant relative to a warmer lamp, such as an incandescent light bulb with a CCT below 3000 K. This shift is relatively large, so a 3000 K illuminant is a poor reference for the equal energy spectrum. The CRI and CQS metrics depend on the much smaller changes in position of the samples relative to a reference lamp with the same CCT.

There is still no widely accepted new system, perhaps due to the complexity of the subject and the increasing complexity of the proposed replacements. The CQS is just one of a number of proposals designed to address the CRI's shortcomings, and is based on a similar design. It has a revised set of 15 colour samples, and it provides more than one value to describe colour rendering properties. The metric CQS Q_a is the system's "lighting quality fidelity metric" which is a direct replacement for the CRI R_a, and is considered to be fairer towards LED lighting.

3.3.2 Gamut area and TM-30

Another approach with some value is to use a metric like CRI R_a together with gamut values, e.g. the area in colour space between a set of colour samples. Gamut Area Index (GAI) is based on the colour space and samples in the CRI system (Rea and Freyssinier-Nova, 2008).

GAI is calculated by joining the green diamonds in Figure 4 with straight lines, for a particular lamp, and comparing the area inside to the area for the equal energy spectrum (Rea, 2013). By definition, this means the GAI for the equal energy spectrum is 100%. The larger the area between the samples, the larger the GAI value and the greater is the theoretical ability of the illuminant to produce more vivid saturated colours towards the perimeter of the colour space.

A similar CQS metric can be calculated based on the 15 CQS colour samples, and a recent proposal with 99 colour samples, TM-30 (David, 2015), is slightly more complex, but shares the same 2-metric system suggested by Rea and Freyssinier-Nova (2008).

The measurement data collected here indicated the GAI method systematically gives higher values for illumination with a higher CCT value. Using an alternative approach to spectral richness without the CCT-bias in gamut area is another option, which is considered next. Gamut metric TM-30 R_g was found to avoid this CCT bias, as suggested by Smet *et al* (2015).

3.3.3 Spectral richness metrics FSCI and Spectral Entropy

Two measures of the “richness” of the spectral power distribution (e.g. Figure 3 above) have been suggested: Spectral Entropy (Price, 2012) and the Full Spectrum Color Index (FSCI) (Rea and Freyssinier-Nova, 2008). Spectral Entropy, denoted H_{Sp}, also avoids the CCT association of GAI but retains other predictive components of a lamp’s colour rendering properties. H_{Sp} is not currently widely used, but follows a promising complementary approach to both colour quality and gamut area calculations (Table 5).

A spectral power distribution that favours any certain wavelengths reduces H_{Sp} from 100%. H_{Sp} gives the mathematical information in the 5 nm resolution spectrum between 380 nm and 780 nm (Price, 2012). A flat spectrum has the maximum information; a single wavelength source (e.g. a single colour laser beam) has the minimum. To make comparisons easier to read, the complementary metric Spectral redundancy, 100% - H_{Sp}, is used in the results in Sections 6-8, with low Spectral redundancy values being associated with better colour rendering.

Table 5: Spectral entropy and spectral richness metrics compared to colour based metrics

Advantage	Details
Simple	Substantially more direct justification and calculation than FSCI and much easier calculations than CRI, CQS, TM-30 and their associated gamut areas.
Robust	High degree of objectivity and results are unbiased by CCT over normal ranges. The ranking between a wide range of different types of lamp is based on central psychophysical principles.
Performance	Spectral entropy evaluates spectral information efficiently. Like other spectral richness metrics, however, it does not value colour preference or use colorimetry functions. This suggests that more than two metrics may be required to fully understand the colour rendering properties of a lamp, including a colour fidelity metric, an advanced gamut metric and a spectral richness metric.

4 Flicker package

The irradiance from many lamps varies regularly several times every second. This package analyses high frequency variations of the irradiance from the lamps. It considers whether the light output modulation is perceptible or may have adverse health effects.

4.1 Flickering light

Flicker has the potential to trigger seizures, migraines, headaches and may be visually uncomfortable or a persistent distraction. The IEEE (Institute of Electrical and Electronics Engineers) in the USA has recently published an extensive review of the effects along with guidance. The IEEE report also highlights gaps that currently exist in the research data relating to health effects (IEEE, 2015).

Modulation is the general term often used to describe the periodic variation of light when considering flicker. However, there is no widely agreed definition of the modulation frequencies and amplitudes that are deemed sufficient to count as flicker. Flicker may be thought of as modulation which has a biological effect. This is the sense of the word used in this report: modulation at physiologically-relevant frequencies and with levels and periodic patterns of variation that together produce a measurable human response.

Evolution optimised our eyes and brains in a non-flickering environment and vision was certainly not evolved to protect our eyes from the effects of prolonged exposures to flicker.

Whilst flicker has often been defined based on conscious human awareness of modulation (i.e. perceptible flicker), this style of definition is now increasingly challenged. It is known that retinal photoreceptors can react rapidly to changes in light levels in a few milliseconds. Throughout human evolution this has been important to recognise threats, which usually moved and reflected changing light patterns towards the eyes. For some time now, physiological and health-related responses to flicker have been documented at higher frequencies than psychophysical experiments based on whether flicker was visible (Brindley, 1962; Wilkins, 1989; Berman 1991). In the latest reviews there are a variety of both known and strongly suspected negative subconscious health effects from flicker (IEEE, 2015).

4.2 Quantifying flicker

For the purposes of this report, two established measures of flicker have been used, known as Percent flicker and Flicker index. These are explained below. Neither one is based on the physiology of the eye, however, so they have limitations. For example 100% Percent flicker at 30 kHz is not physiologically relevant, whereas 40% Percent flicker at 30 Hz certainly is. In fact visual performance can be reduced at frequencies as high as 100 Hz (Jaén, 2011) and 120 Hz (Veitch and McColl, 1995), which are above the frequency at which flicker is considered to become invisible.

Following IEEE (2015) and Wilkins *et al* (2015), this report highlights the need for a practical flicker metric that satisfies both users' and manufacturers' needs. As retinal photoreceptors are the physiological entry point for modulation information, it is proposed here for future work that taking account of photoreceptor reaction times may offer a possible way to analyse imperceptible flicker for protecting against a range of adverse effects, including health effects.

4.2.1 Percent flicker

Percent flicker is the most widely quoted measure of the amount of flicker in the light given off from lamps. It should be given along with the flicker frequency.

As an example, Figure 5 provides the following results from measuring a TH filament lamp:

- **a** There are ten cycles in the period of 0.1 s
- **b** The curve is smooth and has an approximately sinusoidal waveform
- **c** The maximum relative illuminance is around 0.95
- **d** The minimum relative illuminance is around 0.75

The number of cycles is equivalent to one every 0.01 s which corresponds to a frequency of 100 Hz, or twice the UK mains frequency.

Percent flicker is calculated from the difference divided by the sum of the maximum and minimum relative illuminance:

$$\textit{Percent flicker} = 100\% * 0.2 / 1.7 = 11.8\% \qquad (4.1)$$

The Inc and TH lamps had Percent flicker between 9.6% and 12.4% at 100 Hz. For 100 Hz flicker, Public Health England have used 15% (and before as the Health Protection Agency) as a rule of thumb for new lighting technologies, based on these values. In other words, the idea has been that flicker should be no worse from new technologies than from the old ones.

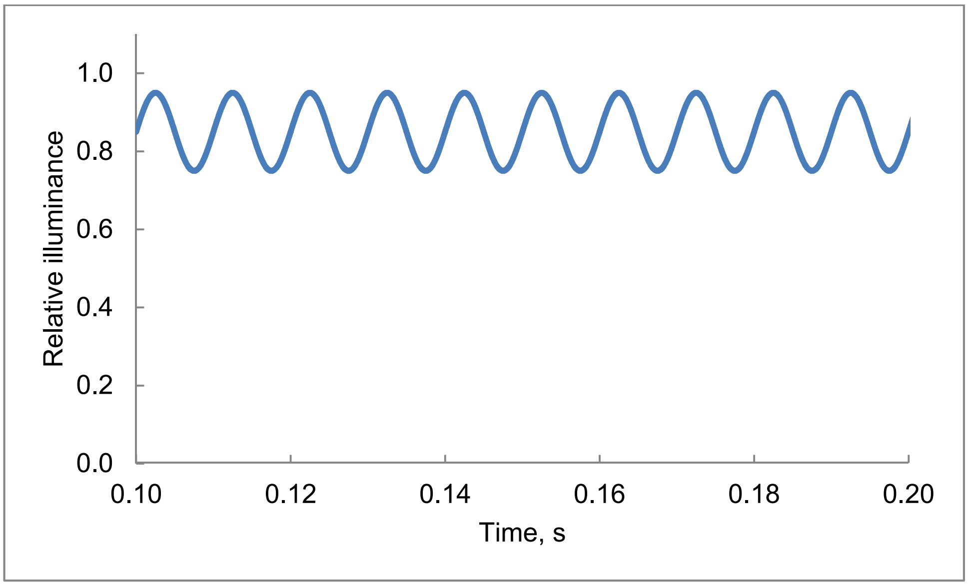


Figure 5: Modulation or flicker of a TH lamp. Equation 4.1 draws its values from this chart. For this reason, the maximum relative illuminance has been normalised to 1.

This provides some justification for avoiding greater levels of flicker, but it has never been possible to point to exact evidence, or a precise physiological justification for the value. One known weakness of using Percent flicker is that the shape of the waveform matters as well as the range of relative illuminance. A square wave is less innocuous than a sinusoidal one, and there are many other relevant factors.

4.2.2 Flicker index

Flicker index attempts to account for the weaknesses in the Percent flicker by comparing the areas in charts like Figures 5 and 6 above and below the average relative illuminance during one cycle (i.e. during 0.01 s if 100 Hz is the lowest modulation frequency).

Figure 6 illustrates two cycles of a complex non-sinusoidal modulation pattern. It is not one of the lights measured in this study, but is used as an illustration. To simplify the calculations, the average relative illuminance has been set equal to 1 (this does not affect the result).

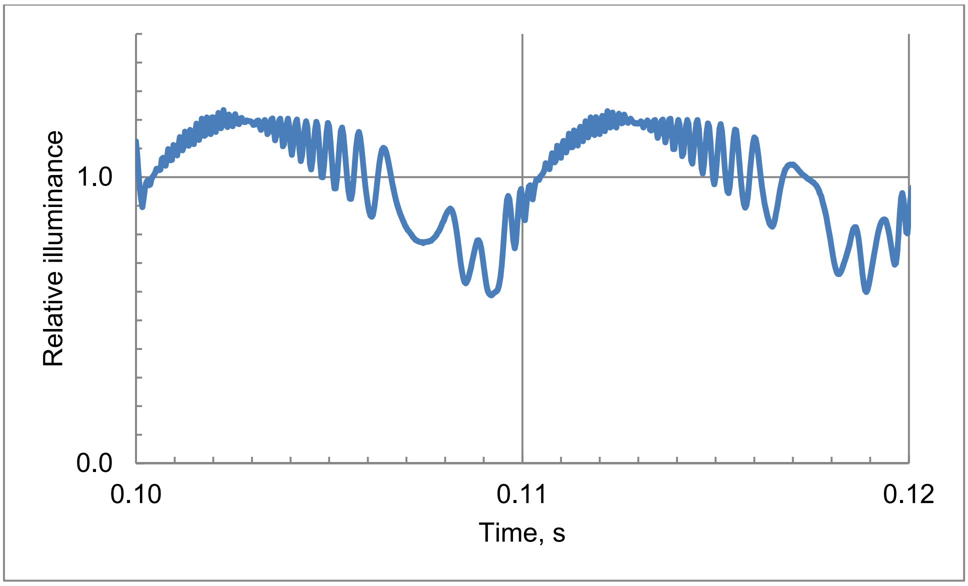


Figure 6: An example complex modulating light time series (here the average relative illuminance is deliberately set to 1 to simplify the calculation in Equation 4.2).

Flicker index is calculated as the difference of the area above divided by the sum of the areas above and below the average relative illuminance:

$$\textit{Flicker index} = 100\% * 0.00074 / 0.01 = 7.4\% \tag{4.2}$$

Flicker index values allow for the shape of the waveform. Although it is an improvement, compared to Percent flicker, it is not clear that it is the right approach. For example, the relationship between the flicker frequency and the frequencies at which there is an effect is still not taken into account. It is also significantly less widely used, although in reality it is not much more complicated to evaluate.

4.3 Safety

Even if it is not deemed as flicker, the pattern of light created by modulation in general may interact with eye movement, object movement and other modulated light sources to create hazards. For example, fast rotating machinery in homes, factories or on roads at night may appear stationary or slow moving when illuminated by a modulating light source. Car and street lights may cause a string of separate after-images as the eye moves. This category of hazard is beyond the scope of this report, but clearly these undesirable effects could be eliminated with modulation-free illumination.

4.4 Dimming and effects on flicker and energy efficiency

Some LED suppliers recommend a specialist LED dimmer, which may cost several times the value of the lamps. The LED dimming capacity with a perfect dimmer has not been tested, and only one lamp was connected to the dimmer at any one time. The flicker-dimming measurement relate only to the inexpensive rheostatic dimmer that was used.

The usual measure of energy efficiency is luminous efficiency. It is based on the visual response to light and the energy used, and these were assessed using spectral power distribution measurements and an electrical power meter (Figure 7). Note that this measure of energy efficiency does not consider other human responses or the colour quality. Taking these aspects into account may shift the preferred balance of wavelengths from the visual response.

Figure 7: The commercial grade electrical power meter used

When dimming incandescent and TH lamps, the colour changes to a warmer colour; this is potentially advantageous for controlling the non-visual stimulus strength of the light environment as the shorter wavelengths are reduced substantially more than longer wavelengths. An in-depth explanation is given in the next Section. Intuitively, it is widely believed that warmer colours may be appropriate in conjunction with dimmer lighting, for creating relaxed environments, e.g. evening illumination. In contrast, the LED lamps selected were not designed to change colour when dimmed.

5 Spectrum package

This package considers the potential role of street lighting to cause sleep disruption at night and the potentially harmful effects of light on the retina. The spectral power distributions of the LED streetlights were measured and photographs of the light emission pattern were taken to support comparisons to other technologies, and as the basis of optical radiation safety assessments.

5.1 Circadian rhythms and non-visual effects of light

Some of the terminology in the field of photobiology is not self-explanatory. Starting with circadian rhythms, this scientific term is often associated with daily periodic biological activities. Circadian literally means “approximately one day” (Andersen, 2012).

The light information for vision follows a different pathway to the light information that governs unconscious responses to ambient light. “Non-visual” or “non-image-forming” photoreception and responses are terms commonly used to describe the photobiological effects related to this second pathway (Lucas *et al*, 2014). Confusingly non-visual refers only to this second pathway from the retina to the brain, and other more direct effects of visible and UV radiation on skin and other tissues are not intended to be included. The damaging effects that very bright light sources can have on the eye, including the retina, are excluded too.

Information in the “non-visual” pathway is regulated by one special type of retinal ganglion cell, or “RGC”. Intrinsically-photosensitive retinal ganglion cells, “ipRGCs” or “pRGCs”, are RGCs which contain a photopigment called melanopsin. Melanopsin in the eye reacts to wavelengths across the visible spectrum and is most sensitive to ambient light at 490 nm (Lucas *et al*, 2014), a wavelength which appears bluish-green. Melanopsin enables ipRGCs to detect light themselves. Like the RGCs used in vision, ipRGCs also receive information about the light derived from the rods and cones.

5.1.1 Regulation of circadian rhythms and disruption of sleep by light

Ambient light levels are the main information our bodies use to synchronise themselves (Andersen, 2012). From the timing of sleepiness, hunger, arousal and our willingness to be active through to the unconscious physiological patterns such as the preparation of our internal organs for daily activities and the ‘decision’ of waking from sleep.

Regular disruption of this complex timing mechanism will lead to tiredness, sleep disruption, below optimal performance, reduced well-being and cumulative effects on long-term health.

The non-visual effects of light can be both positive and harmful to health and well-being. The darkness at night is of equal importance as having adequate light during the day. Following the natural pattern of day and night may be beneficial for health, but this needs to be balanced with the benefits of having light for reading, socialising and personal safety after the sun has set. Artificial lighting, even if it is sometimes over-used or misused, represents a great improvement in our quality of life.

5.1.2 The role of artificial lighting

Daylight quickly reaches much higher levels than typical artificial lighting, but artificial lighting can be extended into the night. When we are indoors, the design of buildings, windows, and artificial lighting, as well as the conditions outside, blinds and curtains, governs the proportion of daylight and artificial light exposures.

As the pattern of the light exposure is changed by artificial light and indoor environments, it is possible for the system of timing derived from light exposures to be disrupted. For example, rotating shift and on-off night shift workers may be exposed to light during the night, and have long periods of relative darkness during the day, when resting. Indoor daytime workers, and residents in nursing homes, schools, prisons and hospitals, typically have a delayed, flattened and elongated light exposure. Compared to natural light levels, which consistently rise in the morning and fall in the evening, this exposure profile reduces the timing information.

Exposure to light in the late evening or at night can have an immediate alerting effect, suppress the secretion of the hormone melatonin, delay the timing and reduce the function of the circadian system. The severity of the effect depends on the dose and timing - how much light, for how long, the spectral power distribution and whether the exposure occurs early, in the middle or late during the night-time (e.g. as reviewed in Chang 2015 and Chellappa 2013).

Laboratory studies in sleep research centres have shown that there are both immediate effects, and effects that are delayed for up to a few days. Changes occur in the quality, timing and length of sleep immediately following the exposure, and further effects will follow due to the change in the behaviour of the regulatory timing system (i.e. circadian rhythms) in preparing the body for activities throughout the following few days.

As the main focus here is potential sleep disruption at night from LED street lighting, this section considers how it may be different from other street lighting as well as from unlit night environments. However, the complexity and remaining uncertainties in the science of non-visual responses applies to any artificial lighting, so it would be wrong for LEDs alone to be associated with these far-reaching effects.

5.2 Blue light hazard and hotspots

None of the LED sources assessed as part of this study emitted any ultraviolet radiation and the thermal hazard was trivial. Therefore, only the blue light hazard was considered.

Blue light is known to be phototoxic for the retina. The International Commission on Non-ionizing Radiation Protection (ICNIRP) regularly reviews the biological evidence and publishes exposure guidelines. Adverse health effects are very unlikely from exposure to light that is within the guideline limits.

Some wavelengths are more effective at causing harm than others, with the peak effect very close to the sensitivity of the short wavelength cones, in other words blue light at around 440 nm. The blue LEDs used in street, office and domestic LED lighting generally emit at around 450 nm to 460 nm. For this reason, there are concerns that the guidelines may be exceeded, especially by lights with hotspots arising from LED chips in direct view.

Glare from lighting, including from hotspots, can be uncomfortable and reduce the visibility of nearby objects even for lighting within retinal safety limits. Visual impairment effects are transient, but should nevertheless be considered as adverse human responses.

5.3 LED street lighting

LED street lighting is being installed in many places around the UK and overseas, so it is important to understand the differences this means for both the lighting quality and any effects on people. Other street lighting technologies have generally been associated with lower CCTs, and sometimes orange light of very low spectral richness, so the appearance of LED street lights with higher CCTs and more day-like colour rendering, is less familiar at night.

The colour rendering of white LED light is typically better than alternative street lighting technologies, which it is argued may help with road and personal safety. The colour qualities of LED lighting may make the lit environment outside more visually stimulating, inviting or distracting, depending on the observer's point of view.

Figure 8: An LED street light taken from the lamps measured.

The non-visual effects of street lighting can be caused by direct light, light reflected from lit objects and the contribution to scattered light from the sky. Light pollution may be cited as a reason both for and against switching to LED street lighting. Light scattering in the atmosphere is greater for shorter wavelengths and the non-visual system is also relatively more sensitive to shorter wavelengths of visible light. The blue LED component is preferentially scattered, and the resulting sky-glow may activate the non-visual system more than other street light conditions. The effect would be greatest for the higher CCT LED street lights, which it is anticipated would increase sky glow by a factor of 5, and lights that emit above a certain angle from the vertical (Baddiley and Wainscoat, 2015). Due to the small emitter size, the light from LED street lights can in theory be carefully directed, so there is a potential for light spill from street lighting to be reduced by LED technology. This places a secondary demand on the preferred beam-shaping optics for LED streetlights – the light source needs to be simultaneously directional and diffuse (without hotspots or glare).

Another advantage LED lighting has for reducing light pollution is the ability to turn on and off almost instantly. The differences in timing are only a few minutes, and the disruptive non-visual effects of light at night continue to accumulate over periods of hours, so this seems a minor advantage for circadian rhythms.

Related to human non-visual responses, the effect on other species in the environment of light at night are of importance for a wider review of the unwanted or unplanned effects of any type of street lighting. Although there are ways in which light at night causes environmental changes that have immediate as well as delayed effects on human quality of life, these are not within the scope of this report.

5.4 LED tablets and e-readers

LEDs are associated with tablets and e-readers, but the light exposures from e-readers are not necessarily equivalent in illuminance or spectrum to an LED for general lighting. News articles often appear relating to people's concerns about these devices and the concerns may spill over to LED lighting with little supporting evidence.

A recent study (Chang *et al*, 2015) showed that reading from these devices for 4 hours before sleep can suppress and shift the onset of melatonin secretion compared to a print book. The results should be interpreted with care, as a very dim room light condition was used for reading from a print book, rather than a well-directed reading light.

PHE recently looked at potential retinal phototoxicity relating to "blue light" from a range of screens including monitors, laptops, mobile phones, as well as tablets and e-reader similar to those in Chang *et al* (2015). In the blue light study (O'Hagan *et al*, 2016) the light measured from these devices was shown to be well within long-established international guidelines or safety limits (ICNIRP, 2013).

6 Domestic-class LEDs – results

6.1 Batch variation

When measuring the spectral irradiance of the domestic LED lamps, the spectral power distributions of the lamps were measured shortly after first being switched on, and then left to stabilise before the representative measurements were taken. Using these data, the illuminance at 300 mm reduced by around 6.6% on average during the measurements, i.e. when operating the lamp for the first time, and the range was between a 0.6% and 16.8% reduction.

However, the measurement timings varied between lamps. For some of the lamps which were not measured in the first few seconds after being switched on, the change in illuminance may be understated, and these results should only be taken as a broad indication of the change in illuminance over around 20 to 30 minutes.

Batch variations in relative spectral power distributions were not significant, at 300 mm directly in front of the lamp and at two further angles for each domestic LED lamp model. Broadly speaking, variations in illuminance remained within a 20% range, and colour variations tended to be associated with the cheaper models. There were, as would be expected, significant variations in illuminance etc. between different angles for any given lamp.

Under dimming, there were no significant colour changes. In contrast, Inc and TH lamps shift to warmer colours when dimmed. Further details relating to flicker and power consumption when dimming are given below (Sections 6.3 and 6.4).

6.2 Colour rendering and CCT

Table 6 sets out the CCT and colour rendering metrics for all the domestic LED models and domestic non-LEDs tested.

The last two models of lamp listed were excluded from the analysis below (see note to the table) as they were purposively selected as being effectively older designs that have largely been replaced. It is expected that customers would tend to avoid buying lamps with visible bare LED chips for aesthetic reasons, despite being cheaper. Whilst the LED element is visible in filament lamps, the source of the light is spatially distributed in a similar way to the filament in an incandescent light bulb.

All of the other 22 models tested stated a CCT value. A large number of the models available had CCT values approximately in the range of 2700 K to 3000 K. The lamps were therefore deliberately selected so that only a small number were outside this range, including a set of three models from the same manufacturer that appeared otherwise identical.

The domestic lamps performed well against the colour space tolerances described in Section 3. All the Duv values were within the range −0.006 to +0.006, and using the equivalent CCT test, only one model had a slightly misstated CCT, measured at 2841 K (unrounded) rather than 2700 K. Notably, this was the lamp with substantially better colour rendering properties than the other lamps, arguably an advantage outweighing this slight discrepancy which essentially only requires a restatement.

All the models with stated CCT values also had CRI R_a values over 80. Rather than increase the scores of all the LED lamps, the switch to CQS Q_a appears to reduce some of these colour quality scores, but typically by less than the reduction in the scores for the two CFLs. The domestic LED lamps' CQS Q_a values were approximately 80-84 (79.9 to 83.8) or better (one model: 88.1), whereas both CFLs scored approximately 75.5 and all the Inc and TH lamps scored approximately 97. A similar picture emerges with the new fidelity metric proposed by IES, TM-30 R_f. Based on limited data, the related gamut area metric, TM-30 R_g, is independent of CCT, although the best domestic result is for the highest CCT lamp tested.

For CCT below 3500 K, TM-30 R_g identifies a relatively inexpensive pearl light bulb with a good all-round colour rendering performance. The other metrics, including H_{Sp}, pick out an alternative LED filament light bulb, this time relatively expensive. Neither model was marked as dimmable.

Table 6: The measured colour rendering statistics and CCTs for the domestic lamps.

Style	CCT, K	CRI, R_a	CQS, Q_a	TM-30, R_f	TM-30, R_g	100% - H_{Sp}
CFL triple tube	2840	80.0	75.1	69.2	**103.3**	28.0
CFL mini spiral	2840	**80.7**	**75.8**	**70.2**	103.0	**27.9**
Incandescent pearl	2740	99.5	97.1	99.5	99.6	5.5
Incandescent filament	2630	99.5	96.5	99.6	99.7	6.3
Tungsten Halogen filament	2690	99.6	96.8	99.6	99.7	6.7
..	2720	**99.7**	**97.3**	**99.7**	**99.8**	5.7
..	2740	99.2	96.6	99.1	99.3	5.4
..	2780	99.5	**97.3**	99.4	99.5	**5.1**
LED filament	2660	81.2	80.9	79.6	88.0	10.2
..	2710	82.6	83.1	83.3	92.7	9.6
..	2730	82.1	82.8	82.7	92.0	10.2
..	2750	83.2	83.7	83.4	92.4	9.6
..	2840	**89.7**	**88.1**	**86.6**	95.9	**7.6**
LED light guide	2610	82.1	80.8	82.2	96.4	9.4
..	2650	81.9	80.9	82.2	96.3	9.6
..	2680	81.0	79.9	80.5	97.5	9.2
..	2750	80.9	81.3	81.4	92.9	9.9
LED pearl	2630	81.6	80.6	81.5	95.6	9.2
..	2680	82.3	81.7	82.8	96.1	9.3
..	2700	80.8	81.5	81.0	90.3	10.3
..	2740	83.4	81.5	82.2	98.2	8.8
..	2950	81.3	82.0	82.1	96.0	9.5
LED multichip and lens	3010	82.5	81.3	81.3	97.0	9.5
..	**4130**	84.1	82.9	82.2	97.3	9.0
..	**6520**	84.9	80.9	80.6	**98.3**	10.1
LED Fresnel and microlens	2780	82.6	83.4	83.6	92.8	10.2
..	**3990**	84.2	83.8	82.0	92.1	9.2
LED microlens	2710	82.4	82.4	83.6	95.1	9.6
..	2920	82.2	82.7	83.2	95.5	9.3
..	3050	82.7	83.1	80.3	90.5	9.4
LED multichip, flat array	2970	60.2	62.8	63.3	83.8	11.4
LED multichip, corn array	2990	62.0	63.8	63.9	85.3	10.2

Note

CCT values in excess of 3500 K ('cool' white) and the best colour rendering metric scores highlighted for each group.

The last two LED lamps are different from the sample in a number of ways: outlying poor colour rendering, the LED chips are directly visible, the CCTs of the lamps were not stated, they were bought from an internet only retailer and they were the least energy efficient and the corn array was also unbranded.

The metrics show there are only minor variations between Inc and TH lamps or between CFLs, but there are clear systematic differences in colour rendering between the different technology types. A similar contrast is evident between LEDs in the different parts of Table 6 and the equivalent tables for office, Table 9, and street lighting, Table 12.

This overall comparison also shows that carefully selected gamut and spectral richness metrics provide independent information about the colour quality. H_{Sp} is regularly in agreement with at least one other metric in identifying the best performing lamp (shown as 100% - H_{Sp}). Colour fidelity and gamut metrics can be seen as specialised tools to study lighting quality based on human colour perception, tools that isolate different aspects of the more general radiometric measures of spectral richness.

6.3 Flicker and dimming

The primary flicker frequency for all the undimmed domestic LED lamps was 100 Hz, often combined with higher frequencies over 1 kHz. In these cases only the 100 Hz flicker was considered physiologically relevant, but Flicker index was taken to be a more robust metric for making comparisons. Both Percent flicker and Flicker index were calculated in Table 7 taking into account several cycles over 0.333 s. The calculation includes all the domestic LED and non-LED lamps and the table appears later in this section.

Shorter periods of data from three examples are shown below in Figure 9 corresponding to Percent flicker values of 97.2%, 46.9% and 10.3% (blue, red and green curves respectively). These values are taken from Table 7. The corresponding Flicker index values are 17.2%, 13.7% and 2.2% respectively. The TH and Incandescent lamps (red and green diamonds) provide a useful benchmark, which have a Flicker index of around 3.5%, whether dimmed or undimmed. Of the examples in Figure 9, only the model shown with the green line provides low flicker levels (almost flicker-free).

Both GU10 and B22 LEDs included low and high levels of undimmed flicker at 100 Hz; the Fresnel lens GU10 LED spots and B22 LED filament light bulbs were low or similar compared to TH and Inc lamps on both flicker metrics. Percent flicker overstated the true effect of the modulation for CFLs tested due to the presence of high frequencies, but this was much less noticeable for most of the LEDs.

Nine models of domestic LEDs tested were marked as dimmable, including three models from the same manufacturer with different colour temperatures. Their output reduced to between approximately 1% and 20% of the maximum illuminance, depending on the model of lamp. This minimum output achieved was below 2% for 2 models, below 5% for 4 more models, including the three with a range of colour temperatures, and the 3 remaining models were only able to be dimmed to 13.3%, 17.9% and 19.9% of their maximum output.

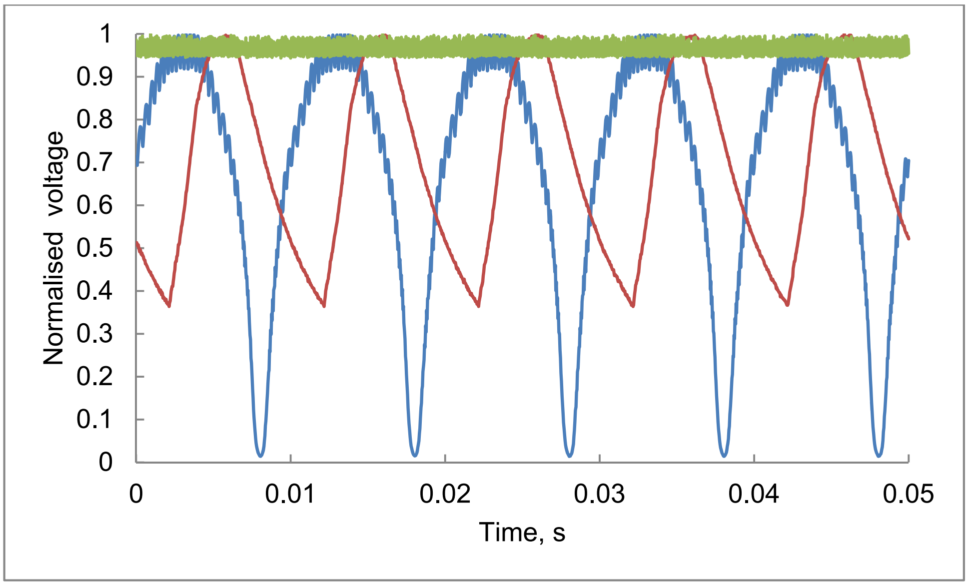
Figure 9 illustrates the main waveforms seen:

a Red shows a relatively smooth, slightly distorted sinusoidal waveform

b Blue shows a broadened version of this, with almost 100% flicker

c Green shows very high frequency modulation that is not physiologically relevant

d Similarly, blue also shows an approximately 3.5 kHz modulation component



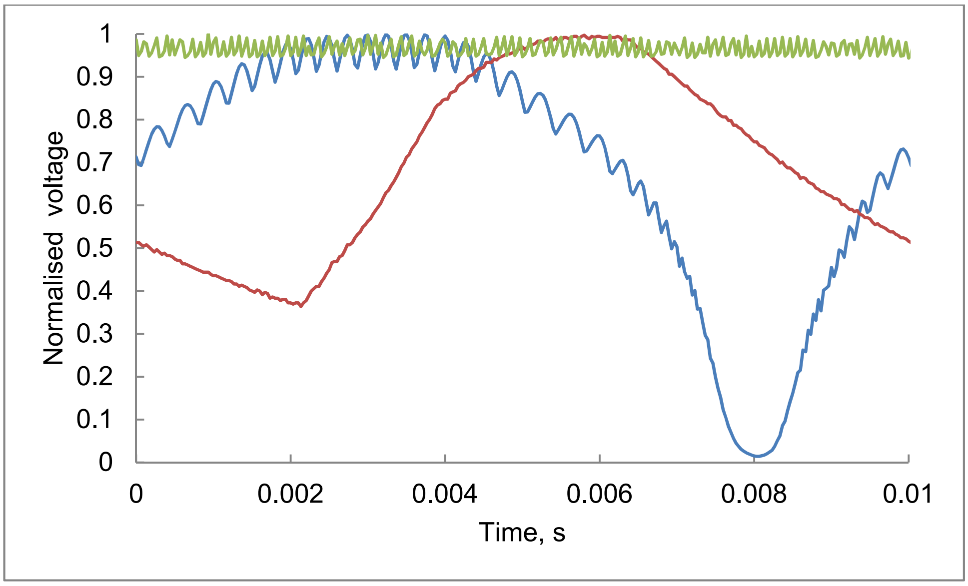


Figure 9: Three examples of modulation measured from undimmed domestic LED lamps. Normalised voltage is proportional to the changing levels of luminous output from the lamp.

Figure 10 illustrates the relationship between flicker from domestic lamps, differences in technology and unit costs for undimmed Percent flicker at 100 Hz and Flicker index ("flicker metrics"). As noted earlier, the TH lamps (red discs, also includes Incandescent light bulbs) provide a useful benchmark.

There are three models with Percent flicker close to 100% and Flicker index close to 17%, which were all similar designs, simply with different CCTs. Counting these as a single model, and using Flicker index, shown in the second panel of Figure 10:

- **a** fewer than half the LED models exhibited lower flicker levels than TH lamps
- **b** unit costs were not linked to lower flicker levels, at least below £10
- **c** even for the seven more expensive LED models only four exhibited lower flicker levels than TH lamps

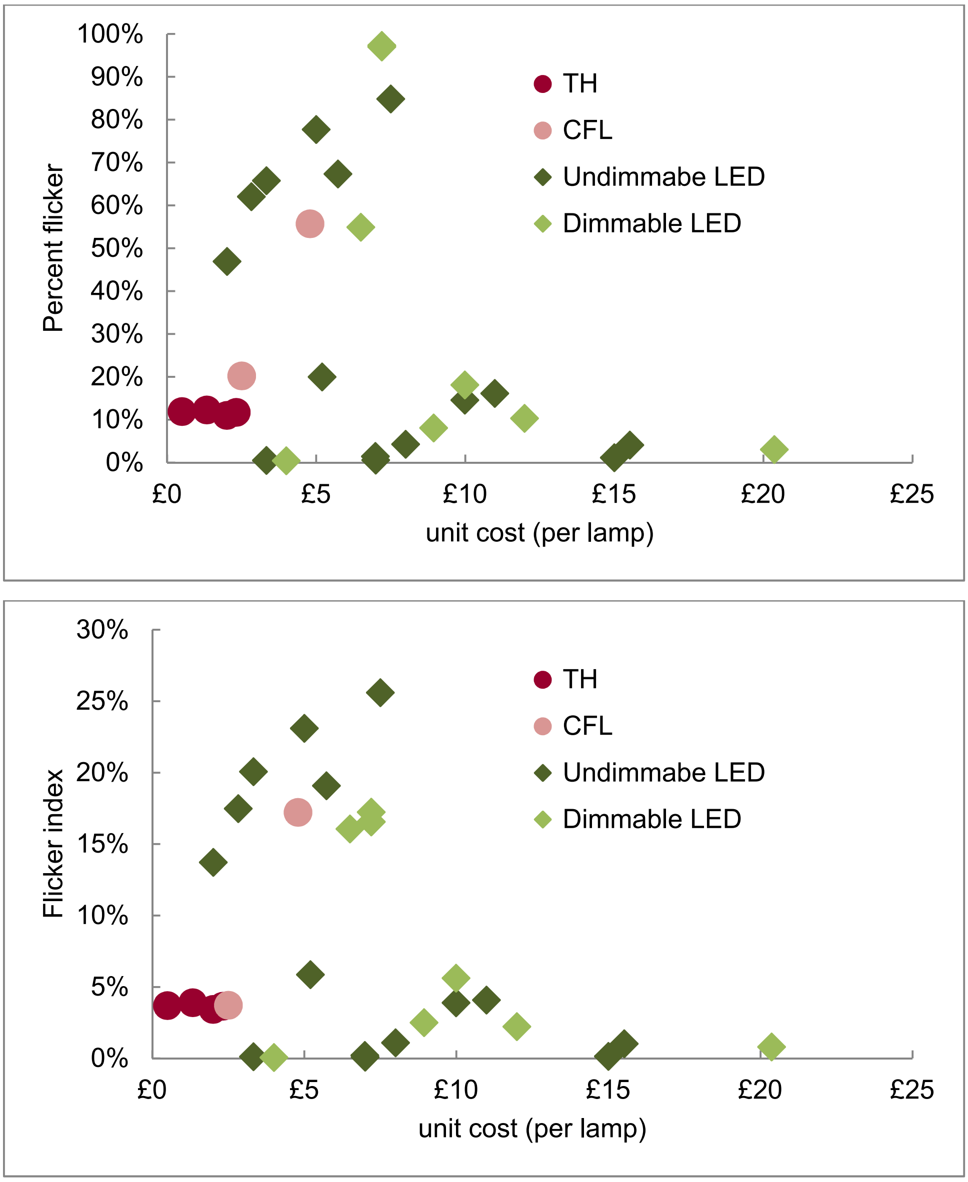
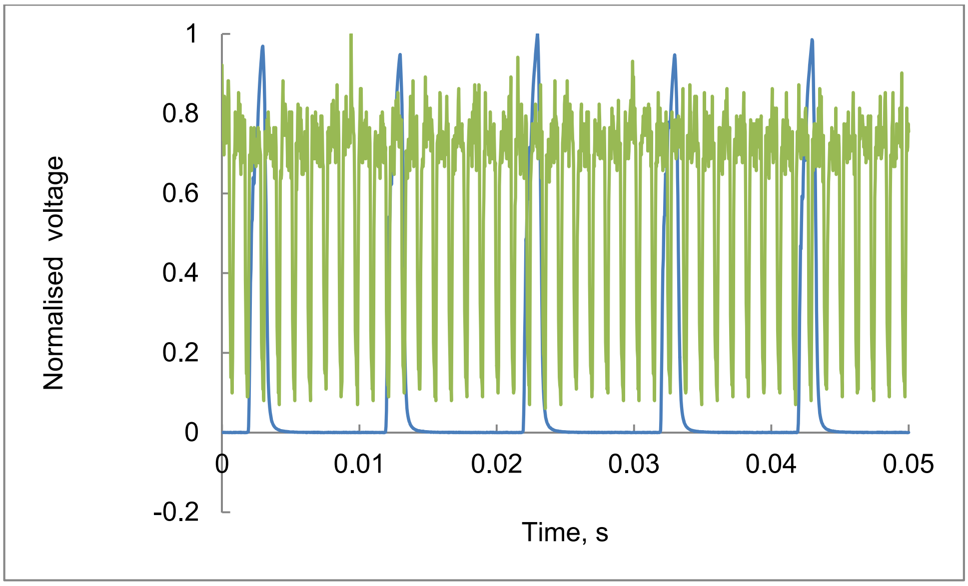


Figure 10: Flicker metrics against unit cost for all the domestic lamp models measured.

It is noticeable that many of the dimmable lamps had high levels of flicker before dimming. Two of the undimmed examples from Figure 9 are shown as dimmed in Figure 11 corresponding to Percent flicker of 100% and 94.8% (blue and green respectively). Figure 11 also illustrates the difference between waveforms with low and high duty cycles (blue and green respectively). The light indicated in blue is off most of the 0.01 s period, whereas the opposite is true for the other LED lamp; low duty cycles increase the problem caused by flicker. This is one reason why Flicker index is a better metric than Percent flicker.

Table 7 only shows the two ends of the dimming range, and the behaviour at 50% and 10% (where possible) was also considered. With the dimmer connected, only four of the nine models provided low levels of flicker (Flicker index < 3.5%, and no component frequencies below 100 Hz) when undimmed, four again when dimmed to 50% of the maximum output, and two when dimmed to 10%. Mostly performance on the Flicker index metric reduced with dimming, but occasionally there were slight improvements in moving to the next level down. Hence Table 7 shows three lamps with low flicker at the lowest level of dimming.



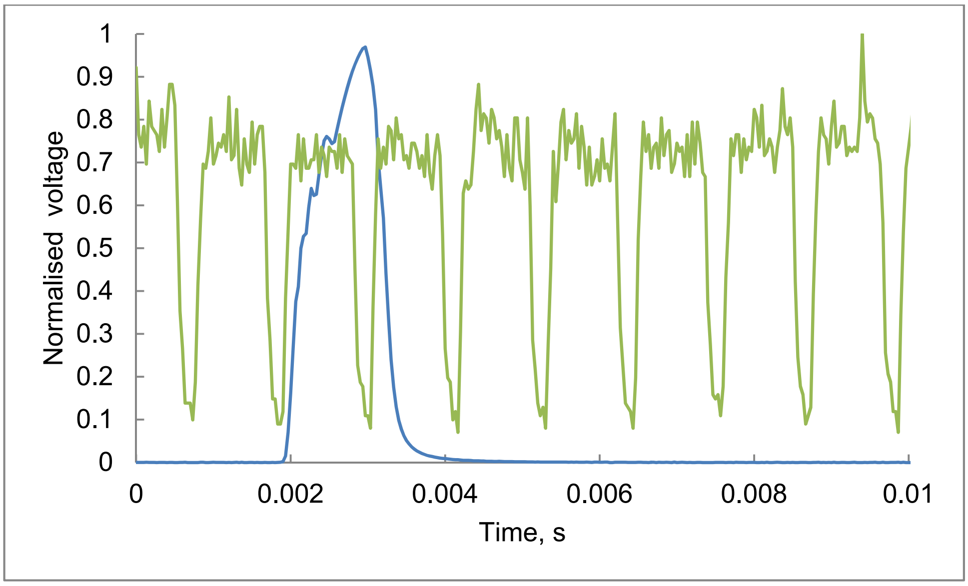


Figure 11: Two examples of modulation measured from domestic LED lamps dimmed to minimum working setting on the dimmer. Normalised voltage is proportional to the changing levels of luminous output from the lamp over time.

It is arguably counter-intuitive that higher levels of undimmed flicker are often associated with the dimmable LED models. However, this may relate to differences in the electronics in dimmable models, and the relationship has a small number of exceptions in both the dimmable and undimmable categories. Together with the results from the office class, the conclusion is that very few LED lamps or panels are available on the market that provide acceptable low-flicker illumination when fully dimmed with an LED-compatible rheostatic dimmer. It would be expensive for individuals to identify these lamps by trial and error; the three dimmable domestic models that performed best on the flicker metric cost approximately £4, £9 and £20 per lamp, compared to the other dimmable LED models at £6.50 to £12 per lamp, so price is also no indication. Note that if more than one LED lamp were connected at once to the same dimmer, the resulting output may be further deteriorated.

Table 7: Flicker measurements and undimmed illuminance at approximately 300 mm.

Style	Undimmed illuminance, lux	Undimmed Percent flicker %	Undimmed Flicker index %	Dimmed to, % of maximum	Dimmed Percent flicker %	Dimmed Flicker index %
CFL triple tube	406	55.7	17.2	-	-	-
CFL mini spiral	622	26.9	5.1	-	-	-
Incandescent pearl	715	-	-	-	-	-
Incandescent filament	589	9.9	3.2	0.2	11.7	2.9
Tungsten Halogen filament	88	11.0	3.4	0.4	12.3	3.1
..	339	11.9	3.7	0.4	14.9	3.6
..	5216	12.0	3.8	2.2	15.1	4.0
..	7688	12.3	3.9	0.8	15.5	4.1
LED filament	33	1.4	0.2	-	-	-
..	86	4.1	1.0	-	-	-
..	88	4.3	1.1	-	-	-
..	94	16.2	4.1	-	-	-
..	65	1.2	0.1	-	-	-
LED light guide	428	54.9	16.1	17.9	68.6	23.7
..	548	18.1	5.6	19.9	35.2	9.7
..	319	10.3	2.2	4.7	94.8	30.7
..	335	0.6	0.1	-	-	-
LED pearl	356	3.0	0.8	1.7	21.4	3.0
..	927	14.6	3.9	-	-	-
..	619	20.0	5.9	-	-	-
..	1124	65.8	20.1	-	-	-
..	1411	69.4	19.5	-	-	-
LED multichip and lens	4135	97.0	16.6	4.6	100.0	86.8
..	4055	97.9	17.3	4.7	100.0	87.2
..	4002	97.2	17.2	4.6	100.0	86.6
LED Fresnel and microlens	4828	0.5	0.1	-	-	-
..	4884	0.4	0.1	13.3	0.8	0.1
LED microlens	12175	8.9	2.8	1.1	14.3	1.8
..	7697	76.6	23.0	-	-	-
..	6912	62.0	17.5	-	-	-
LED multichip, flat array	535	46.9	13.7	-	-	-
LED multichip, corn array	127	84.8	25.6	-	-	-

Note

Undimmed illuminances were measured without the dimmer attached. % of maximum illumination is measured as the ratio of minimum and maximum illuminances achieved with the dimmer attached.

Further details relating to power consumption and dimming are given in Section 6.4 below. Appendix A provides additional details about the flicker measured in the non-LED lamps.

6.4 Power consumption and dimming

Undimmed, the range of actual power consumed is shown in Table 8 for the domestic lamps. This was between 1.5% and 12.5% more than stated for the LEDs. For comparison, the range of the non-LED lighting was from -7.7% to 19.1%. This range of variation for LEDs, 11%, is much less than the 26.8% range for the non-LED lamps tested, even though there were over three times as many LED models included. Domestic LED batch variation was insignificant.

Note that, at around 250 V, the electrical source in the testing laboratory was towards the upper tolerance for UK voltage. This may help explain the power consumption being higher than stated, which may be stated for 230 V. These values are also based on the commercial power meter used, which may plausibly under or over-estimate the power consumption by 5% or more.

In summary, there may be very little difference between the actual and stated power on average and it is the range of results which is of interest. The variations for the LEDs tested were smaller on average than for the non-LED products. Also note that the maximum additional power implied by these values was 0.5 W for LEDs, much lower than the additional 5.3 W for non-LED lighting.

Table 8: Electrical measurements from the power meter and unconfirmed total luminous output.

Style	CCT, K	RMS current, mA	Active power, W	Apparent power |VA|, W	Power factor, %	Total luminous output, lm
CFL triple tube	2840	70	12.0	19.9	60	600
CFL mini spiral	2840	90	13.7	22.8	59	741
Incandescent pearl	2740	240	62.0	62.0	100	700
Incandescent filament	2630	250	62.3	62.3	100	665
Tungsten-Halogen filament	2690	180	45.6	45.6	100	630
..	2720	180	45.7	45.7	100	625
..	2740	170	43.6	43.6	100	300
..	2780	170	44.8	44.8	100	350
LED filament	2660	30	4.2	8.1	51	470
..	2710	30	4.2	8.1	52	470
..	2730	30	4.2	8.1	52	470
..	2750	30	4.2	8.1	52	470
..	2840	30	4.4	8.8	49	400
LED light guide	2610	30	6.2	7.4	79	470
..	2650	20	6.4	7.4	86	470
..	2680	40	6.6	12.4	51	470
..	2750	50	6.8	12.7	53	470
LED pearl	2630	30	7.1	8.1	87	470
..	2680	30	5.7	8.8	65	470
..	2700	50	7.4	14.8	51	470
..	2740	40	5.3	10.5	50	470
..	2950	40	9.3	11.2	81	810
LED multichip and lens	3010	20	5.3	6.3	83	400
..	**4130**	20	5.3	6.3	83	400
..	**6520**	20	5.1	6.0	85	400
LED Fresnel and microlens	2780	40	5.1	10.2	50	370
..	**3990**	20	5.4	7.1	76	346
LED microlens	2710	40	6.1	11.0	55	400
..	2920	40	4.7	11.2	42	345
..	3050	40	4.9	12.0	38	330
LED multichip, flat array	2970	30	3.9	8.4	45	-
LED multichip, corn array	2990	50	4.1	13.7	31	-

Note

Power factor is a dimensionless ratio of Apparent power to Actual power. Apparent power = |VA| has the units of power, W. Engineers may sometimes name the units of Apparent power VA to avoid confusion with Actual power. This unit is equivalent to W. VA is the formula for Complex power, S = VA, rather than Apparent power. Differences between the ratio of actual power to apparent power and power factor, arise as it was not possible to record readings simultaneously.

Figure 12 shows the change in energy efficiency when dimming the domestic LEDs, with the undimmed condition shown to the right. At first some of the lamps increase in efficiency, and some reduce in efficiency as the light is dimmed (tracking individual lines to the left from the right hand side). Relative energy efficiency is the energy efficiency relative to the energy efficiency when the lamp was undimmed (but connected to the dimmer). Dimmable office LEDs had similar results (not shown).

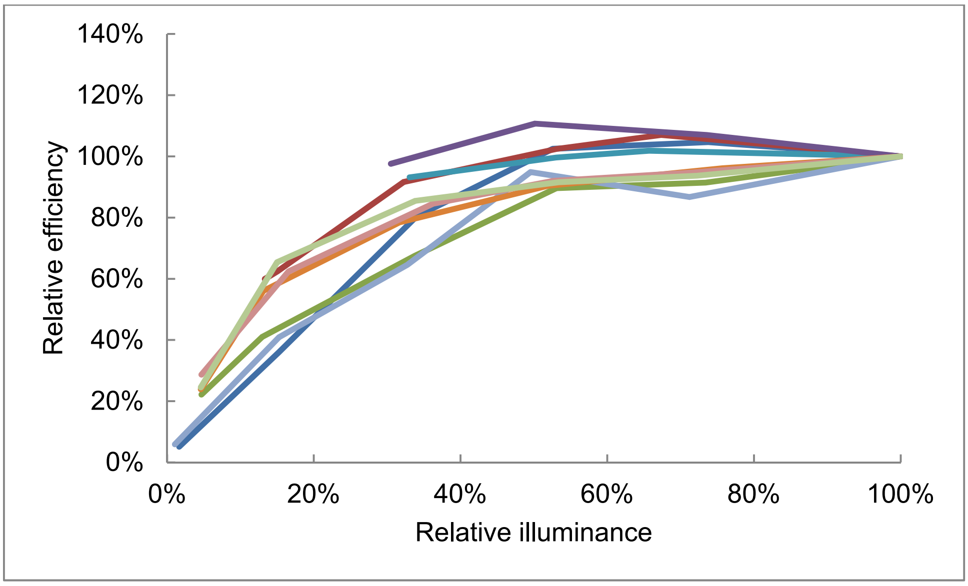


Figure 12: Relative energy efficiency of light production for dimmable domestic LEDs.

Inc and TH types all followed the same curve as Figure 13. Note that, putting colour changes aside, the relative energy efficiency of dimmed LEDs compared favourably to dimmed Inc and TH lamps (the LED curves tend to remain higher to the left of the graphs), down to about 5%.

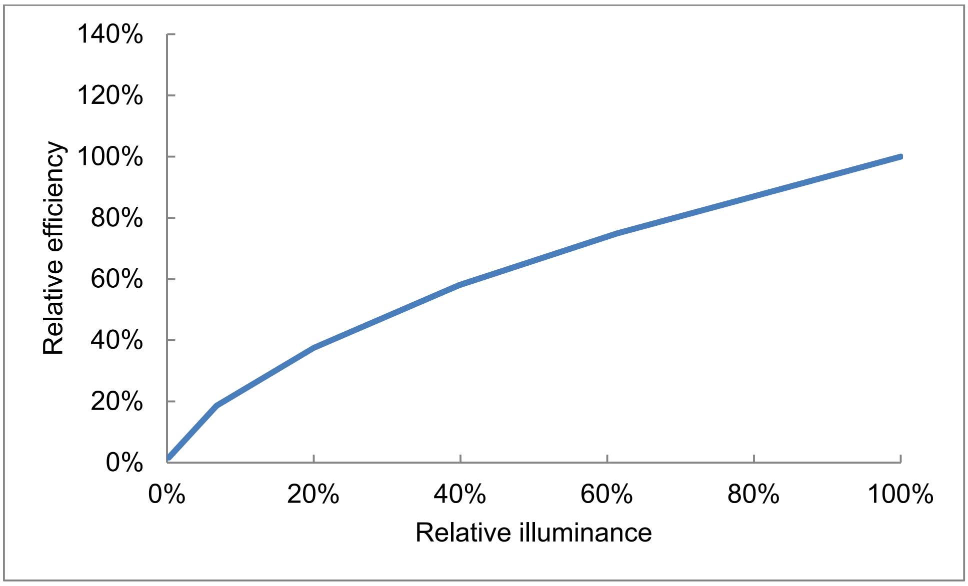


Figure 13: Relative energy efficiency of light production for a 60W pearl Incandescent light bulb.

On continuing to dim, some of the LED lamps eventually turn off, whereas the relative efficiency of others reduces to similar levels as Inc and TH lamps (see Figure 14). The lamps where energy efficiency reduced most quickly (i.e. on the right hand side in Figure 12) were capable of dimming much further, i.e. reaching a much lower percentage of their original output. There appears to be a trade-off between preserving efficiency on dimming and achieving a wider dimmable range (using an LED compatible rheostatic dimmer).

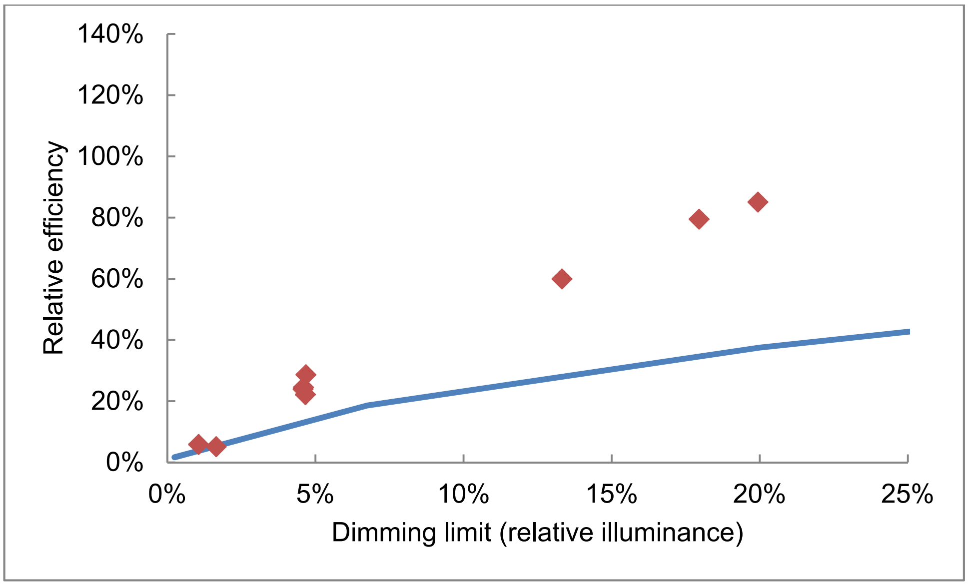


Figure 14: Relative energy efficiency of light production at the dimming limit for dimmable domestic LEDs, with the line for Inc and TH lamps from Figure 13 reproduced for comparison.

6.5 Ocular safety

None of the domestic LED lamps measured emitted ultra-violet radiation or more than negligible amounts of infrared radiation. None of the lamps measured were bright enough to cause retinal damage in normal use at reasonable distances.

Moreover, the assessments carried out place them as comparable with traditional light bulbs.

6.6 Miscellaneous issues

Some of the domestic LED lamps had active components that were not fully enclosed, and this was observed previously outside of this study. Although this does not create an optical radiation hazard, it is obviously necessary for manufacturers to consider all aspects of safety.

There could be safety issues raised if:

a the heatsink is accessible to direct contact

b the wiring for the LED chips is accessible to direct contact or excessive moisture

c the phosphor, the LED chip, or other small parts can fall off or out of the lamp and direct contact may also present a problem for toxic materials, if any.

At least one lamp type tested had holes in the outer casing, presumably for heat management and/or to reduce the chance of condensation. There has been public concern in the UK about electrical safety of some LED lamps (LuxLive, 2015), which was a feature in the BBC's Fake Britain show. As these aspects are beyond the scope of the study, no further investigations were conducted relating to these issues. Compliance with relevant IEC safety standards should prevent these issues arising. Failure to do so may put consumers at risk.

Unexpected condensation was found in the cases of all models of the clear "miniglobe" domestic LED lighting tested. This was not seen in the filament and GU10 models tested or in any of the office or street classes of lighting. It was not possible during testing to investigate whether condensation was ever present in domestic pearl models. The presence of moisture in the casing of an LED lamp (or almost any device) has the potential to degrade various aspects of its integrity over time.

7 Office-class LEDs – results

7.1 Batch variation

The large panels were measured at a distance of 2m, and at different offsets from the centre rather than at different angles. For all the small panels but only for one of the large panels (row 7 in Tables 9, 10 and 11) three lamps were tested from each batch. For the other large 600 mm by 600 mm panels, only one lamp was available. Otherwise the results for batch variation and spatial uniformity of the relative spectral power distributions were similar to the results for the domestic lamps.

Note that one of the small panels had a blue-coloured LED strip surround, producing observable coloured variations in the illumination of objects sufficiently close to the lamp.

7.2 Colour rendering and CCT

Table 9: The measured colour rendering statistics for all the lamps tested, lamp style and CCTs.

Style	CCT, K	CRI, R_a	CQS, Q_a	TM-30, R_f	TM-30, R_g	100% - H_{Sp}
Small panels	2790	80.6	80.3	80.8	95.7	9.5
..	3040	73.6	71.8	69.6	**97.9**	9.7
..	**5040**	**86.3**	**83.5**	**82.9**	95.3	**8.8**
..	**6610**	73.3	71.7	70.6	93.5	10.7
600 mm by 600 mm panels	3110	82.3	**83.5**	**83.1**	96.7	9.1
..	**3860**	81.8	82.7	81.4	**98.0**	**7.9**
..	**3860**	**82.7**	83.1	82.2	96.4	8.0
..	**4810**	82.1	80.9	79.5	91.0	9.2

Note
CCT values in excess of 3500 K (‘cool’ white) and the best colour rendering metric scores highlighted for each group.

Table 9 shows the CCT values and colour rendering metric scores for all the office-class LED panels tested. CCT values were also stated by the manufacturers for seven of the models. One model claimed 3000 K but was measured to be 2791K (unrounded); this was the largest discrepancy measured for any lamp of any class on the CIE 1960 uniform colour space (see Section 3 Figure 4). As for the domestic lamps, all the Duv values were within the range −0.006 to +0.006. No large 2700 K panels were seen that might be considered preferable for evening lighting in residential and healthcare establishments.

Three models of the small panels tested were marked as having CRI R_a values “>80”; of these one of the panels R_a was over 86, and the other two were below 74. The larger panels were loaned; as such they did not come with colour rendering information, but all four models had both CRI and CQS colour quality values over 80. The market for the 600 mm by 600 mm panels appears to have better quality options available, comparable with the domestic market.

Just as noted above for domestic lamps, TM-30 R_f largely reproduces the CQS lighting quality metric results. However it is interesting here that the large panel favoured by the gamut area and spectral redundancy metrics is not the same lamp the CRI metric favours, and that one of the large panels does not retain a score over 80 when switching to R_f.

7.3 Flicker and dimming

The results are shown in Table 10 for the flicker measurements from the undimmed panels.

The small panels exhibiting close to 100% flicker had a similar waveform to the blue lines in Figure 9 above (Section 6.3), and the third small panel listed had a smooth sinusoidal waveform. Again the primary flicker frequency in each case was 100 Hz.

For the large panels, a large contribution to the Percent flicker was caused by high frequency modulation. As a result only the final panel listed had significant flicker assessed using the Flicker index metric, which had a smooth, but slightly distorted, sinusoidal waveform.

All four models of small panels and none of the large panels were marked as dimmable. The output of the dimmable office LED panels tested reduced to around 8.5%, 18%, 17% and 32% of their maximum illuminance (in the order shown in Table 10). As with the domestic lamps, therefore, the higher levels of undimmed flicker were loosely associated with dimmable models.

With one exception dimming the small dimmable panels to the lowest level gave rise to high levels of flicker. Together with the results from the domestic class, the conclusion is that very few LED lamps are available on the market that provide acceptable low-flicker illumination when dimmed with an LED-compatible rheostatic dimmer.

Further details relating to power consumption and dimming are given in Section 7.4.

Table 10: Flicker measurements and undimmed illuminance at approximately 300 mm (small panels) or 2 m (large panels).

Style	Undimmed illuminance, lux	Undimmed Percent flicker %	Undimmed Flicker index %	Dimmed to, % of maximum	Dimmed Percent flicker %	Dimmed Flicker index %
Small panels	3099	1.4	0.3	8.5	14.4	3.0
..	506	100.0	22.2	18.2	100.0	72.6
..	2342	30.6	9.5	32.0	54.5	16.5
..	732	97.5	21.4	17.1	100.0	74.1
600 mm by 600 mm panels	306	6.5	1.2	-	-	-
..	314	13.0	2.8	-	-	-
..	337	1.8	0.2	-	-	-
..	315	35.6	10.5	-	-	-

Note

Undimmed illuminances were measured without the dimmer attached. % of maximum illumination is measured as the ratio of minimum and maximum illuminances achieved with the dimmer attached.

7.4 Power consumption and dimming

The electrical measurements for the office LED panels are shown in Table 11 alongside the manufacturers' stated luminous output, where these were given.

The undimmed power consumption of two models of office lighting panels appeared to be significantly lower than stated (by approximately15%). Both were small panels produced by the same manufacturer. The differences are large enough to suggest there is some unexplained factor. For example, this might be explained if the stated value is over the full lifetime rather than the first use. However, without further investigation, care should be used in interpreting these values.

Table 11: Electrical measurements from the power meter and unconfirmed total luminous output.

Style	CCT, K	RMS current, mA	Active power, W	Apparent power |VA|, W	Power factor, %	Stated luminous output, lm
Small panels	2790	50	12.3	13.3	92	760
..	3040	27	7.7	8.4	92	-
..	**5040**	53	12.4	15.0	83	850
..	**6610**	30	8.5	9.1	93	-
600 mm by 600 mm panels	3110	120	27.3	30.2	91	-
..	**3860**	180	43.8	45.7	96	-
..	**3860**	170	41.2	43.0	95	3825
..	**4810**	170	41.7	43.7	95	3900

These values represent quite different levels of dimming capability. All the dimmable panels performed less well than the median result of the domestic dimmable lamps.

7.5 Ocular safety

None of the office LED lighting measured emitted ultra-violet radiation or more than negligible amounts of infrared radiation. None of the panels measured were bright enough to cause retinal damage in normal use at reasonable distances. Moreover, white LED panels were more innocuous and more visually comfortable than the domestic LEDs, as the emitted light is evenly spread over a larger area.

7.6 Miscellaneous issues

There has been considerable research into using workplace lighting to enhance productivity. Relatively recently, attention has turned to the use of high CCT lighting as a replacement or addition to existing lighting as a means to increase productivity in office environments.

The theory is based on accessing and controlling the non-visual effects of light. The focus is often on short-term attention, alertness and user preferences. Relatively few studies consider effects on circadian rhythms, medium and long-term health effects, absenteeism, seasonal variations or even medium and long-term productivity effects. It remains to be proven what net benefits controlling the non-visual effects of light has on office workers and for their employers, or indeed what intervention strategy is optimal in the medium and longer terms.

In contrast to experimentation with CCT, based on Jaén *et al* (2011) and Veitch and McColl (1995), installing low flicker illumination would appear to be a simple way to improve productivity whilst reducing energy consumption, and without any of the same potential for unplanned consequences.

8 Street-class LEDs – results

8.1 Batch variation

The street lights were measured at a distance of approximately 2m, directly opposite the centre of the luminaire only. Batch variations of the relative spectral power distributions were similar to the results for the domestic lamps and office lamps, with two exceptions.

The power consumption (see Section 8.4 Table 14 below) from one of three lamps provided from one manufacturer was around 10% higher than the other two. These lamps have been analysed as three separate models below. Another lamp from a different batch differed in colour from the other two. From a third manufacturer, only one lamp was provided. In effect, the batch consistency was acceptable in three out of five models where more than one lamp was provided.

None of the street lights were suitable for use with the rheostatic dimmer used in this study, and none were supplied with alternative dimmers.

8.2 Colour rendering and CCT

Table 12: The measured colour rendering statistics for all the lamps tested, lamp style and CCTs.

Style	CCT, K	CRI, R_a	CQS, Q_a	TM-30, R_f	TM-30, R_g	100% - H_{Sp}
Multichip	**3670**	72.5	74.0	71.3	96.2	9.9
..	**3680**	72.6	74.0	71.3	96.3	10.0
..	**3680**	72.0	73.2	69.5	97.1	10.1
..	**3690**	72.3	73.8	71.0	96.2	10.3
..	**3960**	76.2	74.2	72.2	97.9	**9.5**
..	**4320**	75.4	70.8	66.7	**100.5**	10.0
..	**4840**	**77.9**	**74.5**	**73.6**	95.7	9.6
..	**6400**	72.5	71.4	65.4	100.3	10.9

Note

The first, third and fourth were from a single batch. The colour properties were similar, although the lamp in the third row, which had higher illuminance and power consumption, exhibits slightly lower colour fidelity scores and a higher gamut area.

The sixth row represents two out of three of its batch. The third lamp in this batch was excluded. The slight variation in its relative spectral power distribution, colour and CCT (4270 K) only produced minimal changes to the colour rendering metrics.

Table 12 shows the CCT values and colour rendering metric scores for all the street light class LEDs tested.

For one street light model Duv value was -0.0131 (row 6 in Table 12), so the CCT value shown in Figure 4 is not compliant with (ANSI, 2008). The same model, nominally 4000 K street light, had a CCT value of 4321 K (unrounded). All the remaining models had Duv values within the range −0.006 to +0.006.

As the street lamps were loaned, it was not confirmed whether it was advertised as 4000 K. It is also worth noting, this is only slightly misstated in terms of the additional distance in the CIE 1960 uniform colour space (see Section 3 Figure 4).

All the measured CCT values were in excess of 3500 K, despite these colour temperatures providing additional stimulation to the non-visual system. Additional non-visual stimulation may have short term benefits for road safety, but repeated exposure at night may be detrimental to health, depending on the dose, i.e. the light exposure received by a person. The systems and lamps needed to switch between high CCT and low CCT lighting at different hours of darkness would be expensive (certainly at the present time), so lower CCTs are likely to be more suitable for street lighting.

There have been arguments that higher colour temperature street lighting provides better colour rendering. However, the evidence from the street lights measured shows that the CRI R_a and CQS Q_a values were noticeably below 80. For practical reasons, no alternative street lighting technologies were tested, and it is clear that low and high pressure sodium lights do have inferior colour rendering to LED street lighting (Boyce, 2014).

The TM-30 gamut area is higher again for a lamp with a high CCT of around 6500 K, and it may be worth investigating if this metric has a weakness in favour of these high CCT values, perhaps for this type of LED spectra although this was not observed however for the 6600 K small LED panel (Table 9).

Using the data from all classes of lamp measured in this study, R_g appears relatively uncorrelated to either colour temperature or colour fidelity, which is a requirement other gamut area metrics failed, although this is not sufficient by itself to validate the metric. Another concern is the results from the CFL measurements demonstrate that R_g can be high for lamps with 'spikey' spectra, i.e. for sources with undesirable high values of spectral redundancy.

8.3 Flicker

The LED street lights tested had lower flicker than might be expected from other LED lighting technologies (comparing Table 13 to Tables 7 and 10), and lower than the other LED lighting applications on average. It should be noted that the sample tested was not selected randomly and not very wide. Conclusions should be drawn with care, but it demonstrates that it is possible for LEDs and LED street lights to be flicker free, or at least to have the very low flicker levels of the better products tested.

Table 13: Flicker measurements and illuminance at approximately 2 m.

Style	Undimmed illuminance at ~2 m, lux	Undimmed Percent flicker %	Undimmed Flicker index %	Dimmed to, % of maximum	Dimmed Percent flicker %	Dimmed Flicker index %
Multichip	635	13.1	3.5	-	-	-
..	184	2.9	0.4	-	-	-
..	695	12.9	3.4	-	-	-
..	629	16.0	4.2	-	-	-
..	58	2.4	0.3	-	-	-
..	197	0.9	0.2	-	-	-
..	208	6.8	1.8	-	-	-
..	434	3.7	0.5	-	-	-

Note
The LED street lights were not tested for dimming.

The batch analysed as three models in Table 12 (as well as in Tables 13 and 14) had approximately 13% to 16% Percent flicker and Flicker index values of approximately 3.5% to 4.5%. The single lamp had a Flicker index of 1.8%. Flicker index was 0.5% or less for all the other street lights, illustrating that it is possible to design LED lighting which is effectively flicker-free (as was asserted in Section 3). All quoted values are based on 100 Hz flicker, and no other physiologically relevant frequency of flicker was observed.

8.4 Power consumption

The power consumption of one street light appeared to be significantly lower than stated, and one lamp from the varied batch of three had a 10% higher power consumption than the other two. The differences are large enough to suggest there is some unexplained factor. If the consumption on first use is over-stated, it is possible the stated value is over the full lifetime. Without further investigation, care should be used in interpreting these values.

Table 14 shows the electrical measurements from the commercial grade power meter, and illuminance measurements at approximately 2 m. Note that these supplementary measurements were not carried out to the level of accuracy necessary to derive specifications or energy efficiency, but are merely given as a rough indication.

Table 14: Electrical measurements from the power meter and illuminance at approximately 2 m.

Style	CCT, K	RMS current, A	Active power, W	Apparent power |VA|, W	Power factor, %	Illuminance at ~2m, lux
Multichip	**3670**	320	77.0	80.9	94	635
..	**3680**	130	29.8	34.1	87	184
..	**3680**	360	86.3	90.1	95	695
..	**3690**	320	77.0	81.0	94	629
..	**3960**	60	9.4	17.6	54	58
..	**4320**	160	37.5	41.0	91	197
..	**4840**	190	44.1	48.2	91	208
..	**6400**	260	58.8	65.9	89	434

Note
The total luminous output was only stated for the 6400 K model. The stated total luminous output of 7600 lumens was not confirmed as part of this study.

8.5 Ocular safety

None of the street lamps measured emitted ultra-violet radiation or more than negligible amounts of infrared radiation. The LED lamps measured were not bright enough to cause retinal damage in normal use at reasonable distances.

Detailed assessments were made for the street lights. Those assessments do not cover the safety of street lights close-up, for example work in close proximity by service engineers. However, at a distance of 2 m, reaching the exposure limit values for the Blue Light Hazard would require steady fixation for over 2½ hours, based on conservative calculations. LED street lights could, in theory, be fitted close to a window, balcony, ledge or simply close to the ground instead of at a normal height. This should be avoided, or appropriate assessments carried out.

8.6 Miscellaneous issues

The current design of LED street lights consists of discrete bright spots of light, which may result in temporary visual impairment after looking directly into the lamp. Members of the public have complained of debilitating after-images due to exposure to LED street lights, as well as experiencing visual discomfort and distraction. Ayama, 2015, also showed effects from LED street lights of various CCT values to be evaluated by study participants as “dazzling” and “very dazzling” in a realistic scenario.

Hotspots were observed for all the LED street light models tested. As an example, Figure 15 shows one of the units and the inset shows an image of it turned-on, but filtered to reduce the light transmitted by one million times. The hotspots can then be seen clearly. It would be advisable to design the LED luminaire so that hotspots are not visible within the road user’s normal field of view. Although there is currently no agreement on the definition of hotspots that may cause concern, low-cost plastic beam-shaping optics could be used to diffuse the source and to tailor the footprint of the light pattern at ground level. Alternatively, the LEDs could be recessed.

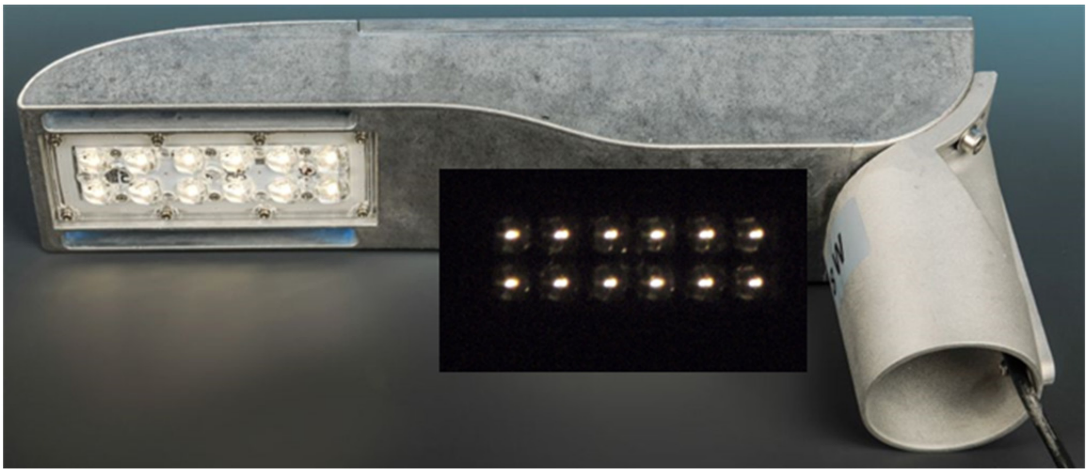


Figure 15: One of the LED street lights tested. The inset shows a light controlled photographic image of the LED chips under attenuation by 6 orders of magnitude. Note that similar hotspots were observed on all the models tested.

9 Conclusions

Light emitting diodes (LEDs) are being promoted for a wide range of lighting applications on the basis of increased energy efficiency compared with some other technologies. However, lighting quality and positive or negative impact on human health are also important. This report presents the results of a study of a varied purposive sample of over 100 LED lamps and luminaires for domestic, office and street lighting. Up to 3 lamps from each model were tested. Altogether there were 38 distinct LED models and 8 models of non-LED domestic lighting for comparison.

The types of LED lamps selected all consisted of a blue LED combined with one or more phosphors to produce a white light source.

Although all were approximately ‘white’, the subtler changes in lamp colour from yellow to blue, as specified by Correlated Colour Temperature (CCT), and from green to purple, as specified by Duv, were examined.

For LED domestic, office and street lighting, CCT values were reasonably accurate, where stated, and Duv values were largely within acceptable bounds. However, colour-matching replacement LED lamps may need manufacturers to provide more colour information than just CCT, and to increase the accuracy of any information already given.

Traditional measures of colour rendering are not always appropriate for LEDs, so the performance of the LEDs was also assessed with some more recent methodologies.

For domestic LEDs, no clear associations were observed in our non-random sample between colour rendering and the lamp cost. However, the colour rendering of domestic LEDs was consistently better than LED street lights, with office panels results being more varied. In addition, the street lights were consistently blue-rich, with CCTs between 3600 K and 6400 K. This finding is somewhat at odds with the arguments often put forward in favour of using LEDs, and using high CCTs, for street lighting in order to improve colour rendering.

Light levels, based on illuminance at 300 mm, reduced by around 6.6% on average shortly after first use (the full range being 0.6% to 16.8%). Batch variations in illuminance at 300 mm, CCT and colour rendering between lamps of the same model were all insignificant.

9.1 Flicker

LEDs are not the only lighting technology that flickers and the electronics that drive LEDs could be designed to eliminate flicker. Despite this, and based on previous experience, when this project started it was expected that flicker would be found in a proportion of the products from across the market.

The LEDs that were found to flicker flickered predominantly at 100 Hz. Percent flicker across all “classes” covered almost the entire range of 0% to 100%. The LED street lights “Class” was an exception, with Percent flicker ranging from 0% to approximately 16%.

Flicker index was used to compare flicker levels in domestic and office LED lighting to non-LED technologies. Around half the domestic and office LEDs, and all the LED street lights, had lower levels of flicker than alternative technologies, but the flicker levels were usually much higher in the remaining domestic and office LEDs.

Below around £10 per unit, there was no link found between unit costs and flicker measures. Although there was less flicker at £10 per unit or above the sample was too small to draw any definite conclusions.

The implications of flicker from the sources tested range in severity from annoying to debilitating. The number of people who are seriously affected by flickering light at 100 Hz is unknown, but it likely to be small. However the general wellbeing and visual performance of a greater number of people may be affected, so it would be prudent to ensure that LED lighting installed in public areas does not flicker, or at least flickers no more than incandescent lamps. If LED lamps sold for the domestic market cause a problem with flicker, it would be appropriate for retailers to accept the return of these lamps.

Another serious consideration for locations where flickering light sources are used is the strobe effect on moving equipment. Although this problem is widely recognised in industry due to issues from magnetically-ballasted fluorescent lamps, the use of flickering light sources in the home could present similar problems. It is reasonably foreseeable that, for example, food mixer blades running at high speed could appear stationary.

9.2 Spectrum

The LED street light measurements were limited to a non-random sample of loaned units provided by manufacturers for the purposes of this study. This section relates to potential adverse visual and health effects of the spectrum and light distribution provided by LED lighting at night.

In normal use at reasonable distances and through normal behaviour, none of the LEDs measured presented any optical radiation hazards as defined by international exposure guidelines, developed by the International Commission on Non-Ionizing Radiation Protection, ICNIRP.

The debate about light pollution at night in residential buildings and the night time environment in general is not unique to LED lighting. However, the roll-out of LED street lighting is accelerating how much of our night time is lit with high-CCT white light sources. This may be concerning, as increased levels of blue light exposure in the evening have been shown to cause melatonin suppression and subsequent phase delays in the melatonin cycle.

LED street lighting could be produced which is low in blue light, and with a diffuse distribution of light at the source. The samples provided for this study proved to be exclusively high CCT LEDs with hotspots of very high luminance and this may indicate the prevailing LED street light design.

However, ascribing these concerns to LEDs in a wider sense risks losing the benefits LED lighting technology may be able to offer street lighting. Therefore, due to the high capital outlay and the potential long-term impact of an inappropriate installation, any new LED street light installations should be subject to an assessment involving qualified lighting professionals, who should consider the conclusions of this report and any future evidence.

9.3 Power consumption and dimming

The stated electrical wattages of the lamps were reasonably accurate, especially compared to other types of lamps; the actual power consumption of two office lighting panels and one street light appeared to be significantly lower than stated. Aside from the street lighting, no significant batch variations in the measured wattage were observed.

Using a commercial grade power meter, the average power factors depended on the application-class: domestic 60% (31% to 87%), office 92% (83% to 96%), and street lighting 84% (54% to 95%).

Dimmable domestic LED lamps and small office LED panels were also measured using a standard rheostatic dimmer to control the illuminance levels. The domestic lamps reached as low as 1% to 20% of their maximum illuminance at the lowest possible setting, with an average limit of 8% of maximum illuminance. The office lighting reached as low as 8.5% to 32%, of their maximum illuminance at the lowest possible setting, with an average limit of 20% of maximum illuminance.

Power factors reduced significantly during dimming, for dimmable domestic lamps using a standard rheostatic dimmer. Flicker generally increased during dimming, in some cases significantly. The flicker from one domestic LED model increased significantly on dimming from below the levels from alternative lighting technologies, to above it. For all but two dimmable LEDs the Flicker index increased significantly (including all four small LED office panels).

9.4 Conclusion

Compared to other existing lighting technologies, LEDs present valid energy efficient options for lighting, and the quality and range of LED lighting has improved significantly over the last five years. However, the differences in costs of the LED lamps tested were not found to be strongly associated with better lighting quality in terms of colour rendering or flicker.

There are signs that manufacturers are beginning to appreciate the human factors that will govern public acceptance and attitudes towards LEDs. There may be further to go yet for this new lighting technology, particularly in the office and outdoor lighting markets. Whilst there are some concerns about LED lighting, they often relate to the current status of a design, or are equally applicable to other lighting types.

It is concluded that flicker from LED lighting may be a risk factor for some adverse health effects in an unknown, but probably small, proportion of the population. Where possible, the flicker should be no greater than would be experienced from incandescent lamps to minimise adverse health effects.

Consideration should be given to reducing the CCT of LED lighting to avoid potential adverse effects on melatonin production in the evening. The science is not yet mature enough to state a threshold CCT that should not be exceeded in general lighting applications. However, some of the sources assessed in this study produced higher CCTs than many people in the UK would find comfortable.

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Appendix A Flicker and other types of domestic lamp

As stated earlier, 100 Hz was the lowest modulation frequency produced by the LEDs tested. This was also true of the Inc and TH lamps and was to be expected, as these lamps have no additional electronic drivers. The flicker frequency for Inc and TH lamps is determined by the effects of the current increasing twice in the 50 Hz AC mains cycle, one time in each direction.

CFLs, which contain electronic drivers, may also flicker at lower frequencies:

a 100 Hz was the dominant flicker frequency (excluding high frequency modulation)

b One model had around 1% flicker at 5 Hz in 2 out of the 3 lamps tested

c For the other CFL model, 2 out of the 4 lamps tested had marginal flicker at 10 Hz, and a third had marginal flicker at 30 Hz.

This report is primarily interested in LEDs, but these CFL results are being followed-up to determine whether further actions are needed.

There are also examples of magnetically ballasted fluorescent tubes flickering at 50 Hz, which the recent IEEE report confirms is inappropriate. This is not uncommon when the ballast (rather than the tube) ages and needs replacing. Magnetic ballasts are out-dated technology, and should be replaced by electronic drivers which are also more efficient (Wilkins, 1989).