Institution: The University of Manchester

Unit of Assessment: 4 (Psychology, Psychiatry and Neuroscience)

Title of case study: A new international measurement standard and guidelines for healthy lighting

Period when the underpinning research was undertaken: 2009 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Timothy Brown	Professor Senior Lecturer Research Fellow	2020 - present 2017 - 2020 2012 - 2017
Robert Lucas	GSK Chair in Neuroscience	2003 - present
Annette Allen	Research Fellow Research Associate	2017 - present 2011 - 2017

Period when the claimed impact occurred: August 2013 – December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Light exposure influences health, wellbeing and productivity but existing lighting regulations and practice do not take such 'non-image-forming' effects into account. Research from the University of Manchester has established a novel method for quantifying these effects and demonstrated the application of this approach for predicting meaningful biological effects of lighting in real world applications. As a result, the new metric has been adopted as a new international lighting standard, forms the basis of a new set of scientific consensus guidelines for healthy lighting and is being used by the lighting industry to develop products and systems maximising the biological potential of light.

2. Underpinning research

In addition to supporting vision, light influences diverse aspects of physiology including hormone secretion, sleep, alertness and mood (so-called 'non-image-forming' responses), making appropriate light exposure essential to health. Underpinning research at the University of Manchester (UoM) has i) established new approaches for dissociating non-image-forming responses from conventional aspects of vision that have played integral roles in the development and acceptance of a new international lighting measurement standard, ii) provided critical proof-of-concept in animals and humans for how the new measurement approach can be practically employed to generate devices that alter the physiological effects of light without compromising visual quality, iii) demonstrated the widespread utility of the new standard for reliably predicting non-image-forming responses, providing the essential foundation for new scientific consensus guidelines on healthy light exposure.

Building on research (led by Lucas) establishing that non-image-forming responses involved a novel retinal light-detector (melanopsin) with distinct properties from the rods and cones essential for vision, Brown developed a new approach to selectively modulate melanopsin signalling using light [1-3]. The approach exploited the unique-bias inherent in melanopsin light detection to short wavelengths (480nm), to generate polychromatic 'white' light conditions that would result in different rates of photon detection by melanopsin (melanopic illuminance) but not for rod and cones responsible for vision. Accordingly, Brown *et al*. showed that these 'melanopsin-isolating' lighting conditions selectively and powerfully controlled the activity of neurons in non-image-forming visual brain regions (and associated physiological responses)

but were without any effect in melanopsin knockout mice. These critical tests of existing assumptions therefore proved the validity and practical utility of a melanopsin-based light measurement approach. Accordingly, this underpinning research [1-3] was central to acceptance of the melanopsin-based measurement by an international expert panel (led by Lucas) as a new strategy for quantifying the effects of non-image-forming effects of light in humans [4].

This research [1-3] also paved the way for equivalent melanopsin-isolating approaches to demonstrate real-world practical applications in humans [5]. Hence, by generating new 5-colour visual displays, Allen and Lucas were able to selectively modulate the melanopic content of movies and show that It was possible to regulate the impact of evening viewing on alertness and hormone secretion, without comprising perceived brightness or colour [5].

By demonstrating its sufficiency to regulate key features of human and animal biology (including the circadian clock that coordinates daily variations in almost all aspects of physiology), the above research constituted strong proof-of-concept for future design of lighting and visual displays that selectively adjust melanopic illuminance to optimise health and wellbeing without compromising visual performance. An important related question, though, has been the extent to which melanopic illuminance alone can predict the extent of non-image-forming responses associated with daily life or whether signals from rods/cones are equally important. Brown tackled this question by applying the new measurement standard to a large scale meta-analysis of existing research into non-image-forming responses in humans [6]. Crucially, this activity confirms melanopic illuminance as a robust and reliable predictor of effects on the human circadian system and hormone secretion for a wide variety of light sources and test conditions. Moreover, it has established a consistent range of light intensities across which such responses operate.

3. References to the research

1. **Brown TM**, Wynne J, Piggins HD, **Lucas RJ**. Multiple hypothalamic cell populations encoding distinct visual information. J Physiol. 2011 Mar 1;589(Pt 5):1173-94. doi: 10.1113/jphysiol.2010.199877
2. **Brown TM**, Gias C, Hatori M, Keding SR, Semo M, Coffey PJ, Gigg J, Piggins HD, Panda S, **Lucas RJ**. Melanopsin contributions to irradiance coding in the thalamo-cortical visual system. PLoS Biol. 2010 Dec 7;8(12):e1000558. doi: 10.1371/journal.pbio.1000558
3. **Brown TM**, **Allen AE**, al-Enezi J, Wynne J, Schlangen L, Hommes V, **Lucas RJ**. The melanopic sensitivity function accounts for melanopsin-driven responses in mice under diverse lighting conditions. PLoS One 2013 8: e53583. doi: 10.1371/journal.pone.0053583
4. **Lucas RJ**, Peirson SN, Berson DM, **Brown TM**, Cooper HM, Czeisler CA, Figueiro MG, Gamlin PD, Lockley SW, O'Hagan JB, Price LL, Provencio I, Skene DJ, Brainard GC. Measuring and using light in the melanopsin age. Trends Neurosci. 2014 Jan;37(1):1-9. doi: 10.1016/j.tins.2013.10.004
5. **Allen AE**, Hazelhoff EM, Martial FP, Cajochen C, **Lucas RJ**. Exploiting metamerism to regulate the impact of a visual display on alertness and melatonin suppression independent of visual appearance. Sleep. 2018 Aug 1;41(8). doi: 10.1093/sleep/zsy100
6. **Brown, TM**. Melanopic illuminance defines the magnitude of human circadian light responses under a wide range of conditions. J Pineal Res. 2020;69:e12655. doi: 10.1111/jpi.12655

4. Details of the impact

Context

Inappropriate light exposure can compromise health and wellbeing by disrupting biological rhythms and sleep, with associated impacts on alertness, performance and mood, and enhanced risk of chronic illness. Given the associated economic impact (~2% gross domestic

product lost due to insufficient sleep across major OECD - Organisation for Economic Co-operation and Development - nations), lighting design must take account of such effects but traditional light measurement systems do not. UoM research has established a method of measuring light that can quantify its ability to elicit such non-image-forming responses [3,4] and defines how they can be adjusted independently of the perceptual qualities of lighting and visual displays [1-3,5,6]. This method has been adopted as a new international lighting standard (CIE S 026/E:2018), forms the basis of new scientific consensus guidelines on healthy lighting and has influenced lighting practice and product design.

Pathways to Impact

The pathway to impact involved close collaboration with Public Health England (PHE), international standards bodies and the lighting industry to establish and implement recommendations and production standards.

January 2013: Lucas led the First International Workshop on Circadian and Neurophysiological Photometry in Manchester, funded by the lighting industry (through ZVEI, the German Electrical and Electronic Manufacturers' Association) and supported by PHE and the relevant European and worldwide standards body (European Committee for Standardisation (CEN) and International Committee for Illumination (CIE)). The group (including Lucas and Brown) approved the new approach for light measurement for non-image-forming responses developed at UoM, published in [4] and which relies heavily on underpinning research [1-3].

2014-2018: Lucas served on CEN and CIE committees for devising new metrics for light measurement (CIE JTC-9 and CENTC169WG13).

August 2019: A follow-up international workshop was held at UoM, led by Brown, supported by CIE and PHE, which agreed quantitative guidelines for healthy light exposure based upon the melanopic measurement system [4] and findings from underpinning research [5,6].

2011-present: Lucas, Brown and Allen present their work to industry and regulators (including Philips Lighting, Apple, Samsung, US Dept. of Energy), at events targeting lighting engineering and design communities (including Smart Buildings (>33,000 attendees); Professional Lighting Design Convention (>1000); Light and Building (>200,000)); and to general and technical media (including BBC TV Breakfast/World News; Electronics weekly (circulation ~41,000); The Lighting Journal (circulation ~2000)).

Reach and significance of the impact

Policy impact – new international lighting standards

The new method of quantifying light (proposed in [4]) resulted in a new SI-compliant system of light measurement [A]. The method was adapted by a committee set up by the International Commission on Illumination (CIE) and accepted by international ballot in 2018. The standard - CIE S 026/E:2018 'International Standard – CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light' [A] - based entirely on the approach described in [4] and citing references [3-4], establishes the appropriate method for measuring light when considering non-image-forming effects.

The CIE full international standard supersedes earlier guidance on light measurement published in initial technical reports and draft standards (*i.e.* to function until the international standard was agreed) from German and European standards agencies, also based on Lucas' research and recommendations [B].

Guidelines for appropriate light exposure in workplaces, educational, healthcare, domestic and residential environments based around the new standard have been agreed by expert scientific consensus (led by Brown) [C] and form the basis of a current CIE position statement and technical report in preparation [D]. Underpinning refs [4-6] (cited in [C]) were central to the resulting consensus.

Guidance for design/application of artificial and architectural lighting released by influential third parties

The method for measuring light arising from work at UoM and now codified in CIE standard CIE S026 is applied by government and non-governmental organisations around the world as the basis for guidance on healthy lighting design. These policies apply to a wide range of domestic, public, and industrial settings, aiming to reduce the harmful effects of artificial light and disrupted lighting schedules by adjusting light exposure as quantified by the standard. Specifically they all recommend the use of high melanopic light during the day and/or low melanopic light during the night. Examples include:

- **International Well Building Institute (IWBI)**: administers the WELL Building Standard – a performance-based system for measuring, certifying, and monitoring features of buildings that impact the health and wellbeing of the people who live, work, and learn in them, currently being applied to projects encompassing 669,000,000 ft^2 across 64 countries. Lucas *et al*., 2014 [4] informed v1 of the WELL Building Standard [E(i)] (launched October 2014), the first standard of its kind that focuses solely on the health and wellness of building occupants.
- **US Department of Energy**: produced fact sheets in 2014 aimed at anyone considering LED lights – as used by local government in terms of road lighting, but also all other branches of government and industry and the general public [E(ii)].
- **The Building Research Establishment:** a non-profit UK-based organisation supporting research and education to provide a better built environment. Released a fact sheet 'Lighting for Circadian Rhythms' [E(iii)] based on Lucas at al. 2014 [4] and codified in CIE S026.
- **National Institute for Public Health and the Environment (Netherlands):** produced two reports on the health impacts of evening light exposure; RIVM 2017-01-16 - Screen use and blue light: Extent of exposure and relationship with sleep [F(i)] and RIVM-2018-0147 - Screen use, blue light and sleep [F(ii)]. Both cite [4] and use the associated melanopsin measurement approach.

Product design

The lighting device and measurement industries are increasingly adapting their products to account for non-image-forming effects of light. In the case of lighting design, this involves modulation of output in the 'blue' part of the spectrum, the most obvious current examples being the computer, tablet and smartphone screen yellowing apps widely applied to minimise sleep disruption, *e.g.* f.lux [G]. Numerous 'healthy lighting' products are now being sold, based on CIE S026 or previous drafts of the standard (*e.g.* [H]), and the market for such products is predicted to reach USD3,500,000,000 by 2024. Instruments for measuring light in melanopic units are also appearing (*e.g.* [I]).

5. Sources to corroborate the impact

A. Published international standard on light measurement from the CIE (CIE S 026/E:2018) (2018): 'International Standard – CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light' – *based entirely on the metric for measuring light in melanopic units proposed in underpinning reference [4] and also citing [3].*

B. Draft versions of the standard and initial technical reports which preceded the international standard CIE S 026/E:2018, *based entirely on underpinning reference [4]:*

(i) CIE Technical Note on new light measurement standard. CIE TN 003:2015 (2015): 'Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013' – *Brown and Lucas are named as Scientific Advisors on page 3.*

(ii) Draft standard DIN SPEC 5031-100:2015-08 (2015, in German): 'Optical radiation physics and illuminating engineering - Part 100: Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra'.

(iii) CIE Draft International Standard DIS 017/E:2016 ILV (2016): 'International Lighting Vocabulary, 2nd Edition'.

(iv) CEN Technical Report PD CEN/TR 16791:2017 (2017): 'Quantifying irradiance for eye-mediated non-image-forming effects of light in humans'.

C. Guidelines for appropriate light exposure *based around the new international standard CIE S 026/E:2018 and agreed by expert scientific consensus (led by Brown)*: **Brown, TM**, Brainard, GC, Cajochen, C, Czeisler, CA, Lockley, S, **Lucas, RJ**, Münch, M, O'Hagan, JB, Peirson, SN, Price, L, Roenneberg, T, Schlangen, LJM, Skene, DJ, Spitschan, M, Vetter, C, Zee, PC, Wright KPJr. (2020). Recommendations for healthy daytime, evening, and night-time indoor light exposure. *Preprints* 2020, 2020120037 (doi: 10.20944/preprints202012.0037.v1) - *draws heavily on underpinning reference [6] and also cites underpinning references [4] and [5].*

D. Letter from CIE (1 December 2020), confirming Brown and Lucas's pivotal roles in establishing expert-scientific consensus lighting recommendations based on the new light measurement standard, including the CIE Position Statement on Non-Visual Effects of Light - Recommending Proper Light at the Proper Time, 2nd Edition, October 2019, detailing the CIE Technical Report in preparation on the consensus recommendations from the 2019 Manchester workshop (*led by Brown and published in [C]*).

E. Guidance on healthy lighting design based on the method for measuring light arising from the UoM research and codified in the International Standard CIE S 026:2018:

(i) The WELL Building Standard (v1 with May 2016 addenda) - *advice on the non-visual impact of light is based upon underpinning reference [4]*.

(ii) US Department of Energy fact sheet: PNNL-SA-102586 Solid-State Lighting Technology Fact Sheet: 'Lighting for Health: LEDs in the New Age of Illumination' (May 2014) – *based entirely on underpinning reference [4].*

(iii) Building Research Establishment fact sheet 'Lighting for Circadian Rhythms' (October 2019) – *based on underpinning reference [4].*

F. National Institute for Public Health and the Environment (Netherlands) reports on the health impacts of evening light exposure, *both citing underpinning reference [4]*:

(i) RIVM 2017-01-06 – 'Screen use and blue light: Extent of exposure and relationship with sleep'.

(ii) RIVM-2018-0147 – 'Screen use, blue light and sleep'.

G. f.lux screen yellowing app: *cites underpinning reference [4] and CIE S 026/E:2018*.

H. 'Healthy lighting' products that reference the International Standard CIE S 026:2018 or previous drafts of the standard:

- Seoul Semiconductor's SunLike Series Natural Spectrum LEDs – *cites the International Standard CIE S 026/E:2018*.
- Light Design for WELL with BIOS SkyBlue – *references the WELL building standard and "melanopic lux" proposed in underpinning reference [4].*
- Zumtobel Human Centric Lighting with tunableWhite - *cites CIE S 026/E:2018, DIN SPEC 5031-100 and the WELL Building Standard*.
- Samsung Human Centric Lighting Solutions (Optimized Light for Circadian Rhythm Synchronization) - *based upon 'melanopic ratio', a direct application of UoM's melanopsin metric [4] standardised in CIE S 026/E:2018*.
- Osram LED Components for Circadian-friendly Lighting - *cites the draft standard DIN Spec 5031-100*.

I. Light measurement systems and devices for measuring light in melanopic units (*proposed in underpinning reference [4]*):

- Gigahertz-Optik GmbH Spectral light meter with flicker measurement function – *cites the International Standard CIE S 026:2018.*
- Solemma Adaptive Lighting for Alertness (ALFA) - A new circadian lighting design software - *based entirely on the melanopic lux metric proposed in [4].*
- JETI LiVal Radiometric Software – *cites the draft standard DIN SPEC 5031-100:2015-08.*