



SOFTWARE TOOL ARTICLE

UPDATE ***luox*: novel validated open-access and open-source web platform for calculating and sharing physiologically relevant quantities for light and lighting [version 2; peer review: 2 approved]**

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Abstract

Light exposure has a profound impact on human physiology and behaviour. For example, light exposure at the wrong time can disrupt our circadian rhythms and acutely suppress the production of melatonin. In turn, appropriately timed light exposure can support circadian photoentrainment. Beginning with the discovery that melatonin production is acutely suppressed by bright light more than 40 years ago, understanding which aspects of light drive the 'non-visual' responses to light remains a highly active research area, with an important translational dimension and implications for "human-centric" or physiologically inspired architectural lighting design. In 2018, the International Commission on Illumination (CIE) standardised the spectral sensitivities for predicting the non-visual effects of a given spectrum of light with respect to the activation of the five photoreceptor classes in the human retina: the L, M and S cones, the rods, and the melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs). Here, we described a novel, lean, user-friendly, open-access and open-source platform for calculating quantities related to light. The platform, called *luox*, enables researchers and research users in chronobiology, sleep research and adjacent field to turn spectral measurements into reportable quantities. The *luox* code base, released under the GPL-3.0 License, is modular and therefore extendable to other spectrum-derived

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1

2

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report



report

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quantities. *luox* has been endorsed by the CIE following black-box validation.

Keywords

chronobiology, sleep research, environmental psychology, CIE, International Commission on Illumination, light, ipRGCs, melanopsin, cones, rods, alpha-opic radiance, alpha-opic irradiance, equivalent daylight illuminance, equivalent daylight luminance, EDI, EDL, non-visual effects of light, spectrum, web platform, open access, open source

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Any reports and responses or comments on the article can be found at the end of the article.

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Competing interests: M.S. was an unpaid member of the Joint Technical Committee (JTC9, “CIE system for metrology of ipRGC influenced light response”) within the International Commission on Illumination (CIE), which developed the CIE S 026/E:2018 standard, between 2016 and until its conclusion in 2018, and is currently an unpaid member of Technical Committee TC 1-98 (“A Roadmap Toward Basing CIE Colorimetry on Cone Fundamentals”). M.S. was also an unpaid advisor to the Division Reportership DR 6-45 of Division 3 (“Publication and maintenance of the CIE S026 Toolbox”). Between 2017 and 2020, M.S. was elected Chair of the Color Technical Group within the Optical Society. Since 2020, M.S. is an elected member of the Daylight Academy. None of the aforementioned activities is paid and constitutes a competing interest. Over the past two years (2019-2020), M.S. has received industrial research support from f.lux software LLC, Ocean Insight, and BIOS Lighting. M.S. is a member of the Technical Advisory Board of Faurecia IRYStec Inc. None of the aforementioned activities constitutes a competing interest and they listed simply for transparency. M.H. is co-founder of f.lux software LLC, which makes a software package called “f.luxometer” to measure spectral quantities. The contribution to this work does not impact on revenue or operations of f.lux.

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REVISED Amendments from Version 1

This updated version includes a description of the CIE endorsement and validation.

Any further responses from the reviewers can be found at the end of the article

Introduction

Light profoundly affects human physiology and behaviour¹. Exposure to light in the evening and at night can suppress the production of melatonin^{2–6} and delay phase of the circadian rhythm^{3,7–13}, while morning light exposure advances the circadian phase^{10–12}. Additionally, exposure to light modulates alertness^{14–16}, and there is emerging evidence for a direct role of light in regulating mood^{1,17,18}. These ‘non-visual effects’ of light are mediated by a subset of the retinal ganglion cells which express the photopigment melanopsin^{19–24}, a short-wavelength sensitive pigment with a peak spectral sensitivity near 480 nm^{20,25,26}. Importantly, melanopsin provides a pathway for signalling environmental illumination that is independent of the ‘canonical’ photoreceptors in the retina, the cones, of which there are three types that differ in their spectral tuning (the, L, M and S cones), and the rods.

The modulation of non-visual physiology by melanopsin is supported by a set of key studies in the early 2000s led by Brainard and colleagues^{4,5} (data reanalysed in 27–29), and by Skene and colleagues⁶ (data reanalysed in 27) which determined the action spectrum for acute human melatonin suppression during night-time light exposure, showing a clear short-wavelength peak. Action spectrum data for circadian phase shifting is limited^{7,30,31}, not least due to the complexity in implementing protocols to assess light-induced circadian phase shifts, though existing data are consistent with a dominant role of melanopsin^{7,29–31}. Furthermore, melatonin suppression responses to bright evening light persist in patients without demonstrable cone and rod function^{32,33}, clearly supporting the role of melanopsin in non-visual responses in retinal and ocular disease³⁴.

While many fundamental aspects of the non-visual effects of light have been characterised in experimental and field studies, there are many unknowns and understanding the effects of light on human physiology and behaviour remains a highly active area of investigation. Recent studies have investigated temporal integration properties of the human circadian system^{8,35–39}, and have exploited silent-substitution techniques or metameric lights to characterise the non-visual response to pairs of lights that differ only in melanopsin stimulation^{40,41} or S cone stimulation⁴².

With many response characteristics still being under investigation, mechanistic insights about the non-visual effects of light exposure are now increasingly finding their way into real-world applications. A recent international consensus statement identified criterion light levels to minimise the detrimental effects of light at the wrong time and maximise the

positive ones⁴³. At the same time, principled approaches to realising physiologically inspired lighting based on scientific evidence are emerging (e.g. see 44). Both the development of recommendations and applying basic neuroscience findings in architectural lighting design require the ability to use a common currency to quantitatively describe the effect of light on people.

Science is a cumulative effort that requires the aggregation of studies to facilitate meta-analytic efforts and evidence synthesis (see, e.g., 27 and 45 for recent efforts to aggregate data). To enable a clear interpretation of the results and “future-proof”⁴⁶ research efforts requires adequate documentation of study conditions going well beyond current standard practice. A recent examination of 71 studies on the biological effects of light revealed that 55% (39/71) did not report any information about spectrum, and an overwhelming majority (87%; 62/71) only reported light levels in lux⁴⁷, representing a quantity weighting L and M cone activity, which is inappropriate given the converging evidence of the dominant role of melanopsin^{27–29,48}. Furthermore, there is large variability in what is considered “dim light”, with light levels called “dim” in practice spanning almost two log units⁴⁷. Since a key biomarker for circadian phase, the “dim light melatonin onset” (DLMO)^{49,50}, hinges upon data collection in dim lighting conditions.

Recommendations and guidelines for the measurement, recording and reporting of the lighting conditions have been made independently by Spitschan *et al.*⁵¹ and Knoop *et al.*⁵², with a more recent comprehensive guide, also encompassing study characteristics other than light, being published by the International Commission on Illumination (CIE)⁵³. However, while recommendations and guidelines are quite important, they are only one aspect, and to make them easy to be applied, tooling is often required. To support adoption of the recent CIE standard S 026⁵⁴, the CIE recently released an Excel spreadsheet⁵⁵, requiring the proprietary Excel software. There are also a range of tools available for calculations to run locally on the user’s computer, such as the Python package `colour`, requiring a functional Python installation.

Here, we introduce a novel web-based platform called *luox* for calculating, reporting and sharing physiological quantities related to light. All calculations are performed in a modern browser and require no software installations on the user side.

Methods**Implementation**

luox (RRID: SCR_020994) is implemented in JavaScript, HTML & CSS using `React` and `chart.js`. The source code is available under the GPL-3.0 License at [GitHub](https://github.com/luox)⁵⁶. luox is deployed at <https://luox.app/>. Further details on implementation are given on the [about](#) page.

Operation

luox can be accessed [online](#) using any contemporary browser. The operational workflow is shown in [Figure 1](#). The user measures an irradiance or radiance spectrum using their spectroradiometer and stores the spectrum in a CSV file. This

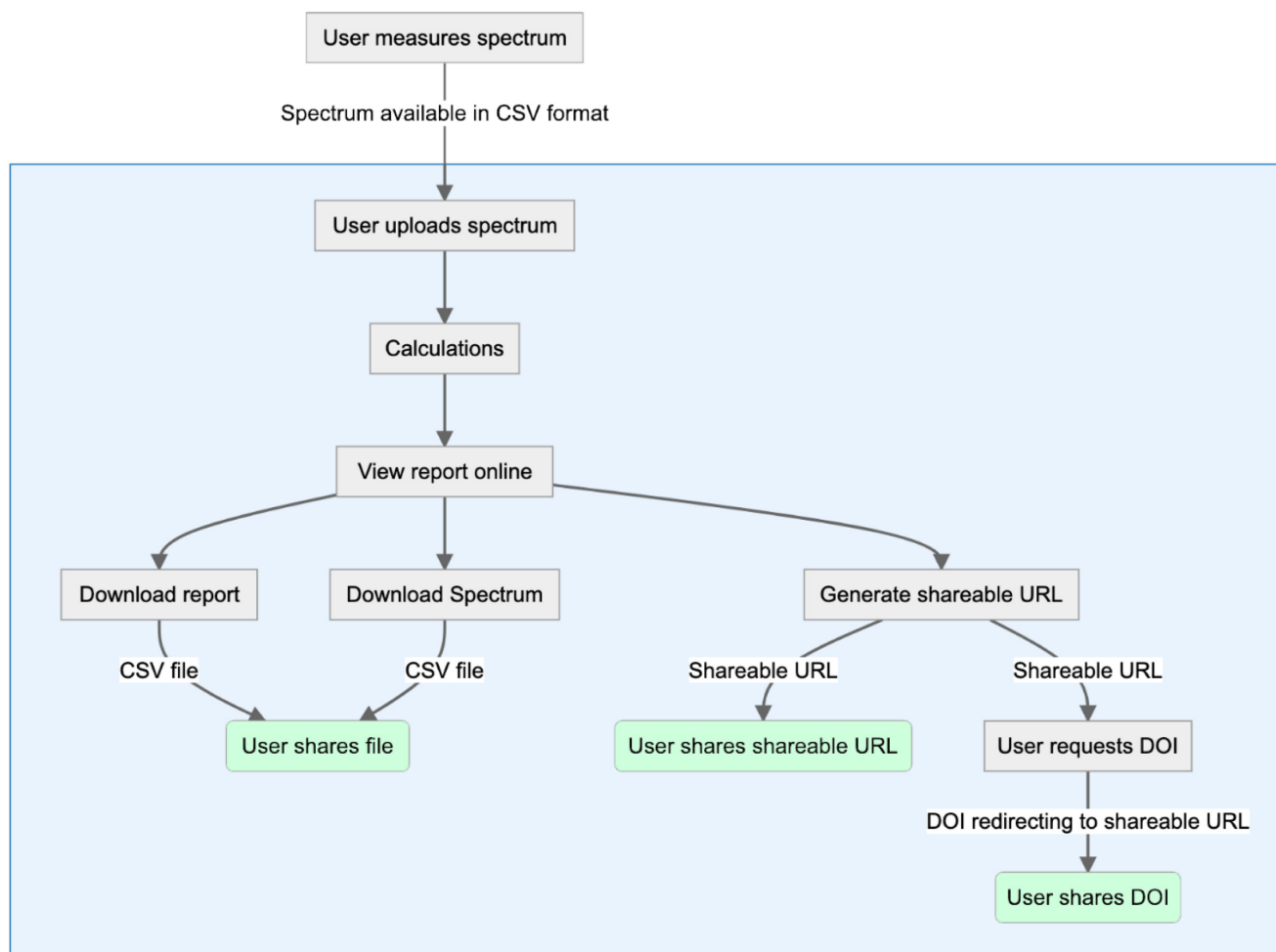


Figure 1. Workflow diagram.

file is then uploaded into the platform, which performs a series of calculations (detailed below) and visualises the spectrum in a report. This report can then be viewed in the browser, but also downloaded as a CSV file for sharing, e.g. as supplementary CSV file. The platform also allows for downloading the spectrum again as a CSV file. In addition, luox generates a shareable URL, which encodes the uploaded spectra in a URL (see below). A DOI can be requested which redirects to the shareable URL. The graphical user face is shown in [Figure 2](#).

Use case

The luox platform includes a wizard, which details the requirements for files and expected file formats, and also includes a [sample file](#) containing three CIE Illuminants in the F series in 5 nm spacing. Upon uploading the file, calculations are performed, giving access to the workflow described above and in [Figure 1](#).

Calculations

The platform implements as a set of photometric, colorimetric, colour rendition and α -opic calculations based on a

user-supplied irradiance [$\text{W}/\text{m}^2/\text{nm}$] or radiance [$\text{W}/\text{m}^2/\text{sr}/\text{nm}$] spectral power distribution $S(\lambda)$. It is assumed that the user has

Photometry. luox implements the following photometric calculations:

- *Illuminance [lux] or luminance [cd/m^2].* Illuminance (for irradiance spectra) and luminance (for radiance spectra) corresponds to the spectrum weighted by the photopic luminosity function, $V(\lambda)$, and multiplied by the constant $683 \text{ lm}/\text{W}$. $V(\lambda)$ is based on psychophysical measurements (for a review, see [57](#)) and was first standardised by the CIE in 1924⁵⁸ and forms the basis of current photometry⁵⁹.

Colorimetry. We implement the following colorimetric calculations:

- *CIE 1931 xy chromaticity (2° observer).* The chromaticity coordinates are a way to identify the colour appearance of a spectrum. The CIE 1931 xy chromaticity diagram, also called the horseshoe, is based on the XYZ colour matching functions standardised by the CIE in 1931⁶⁰ based on 2° colour

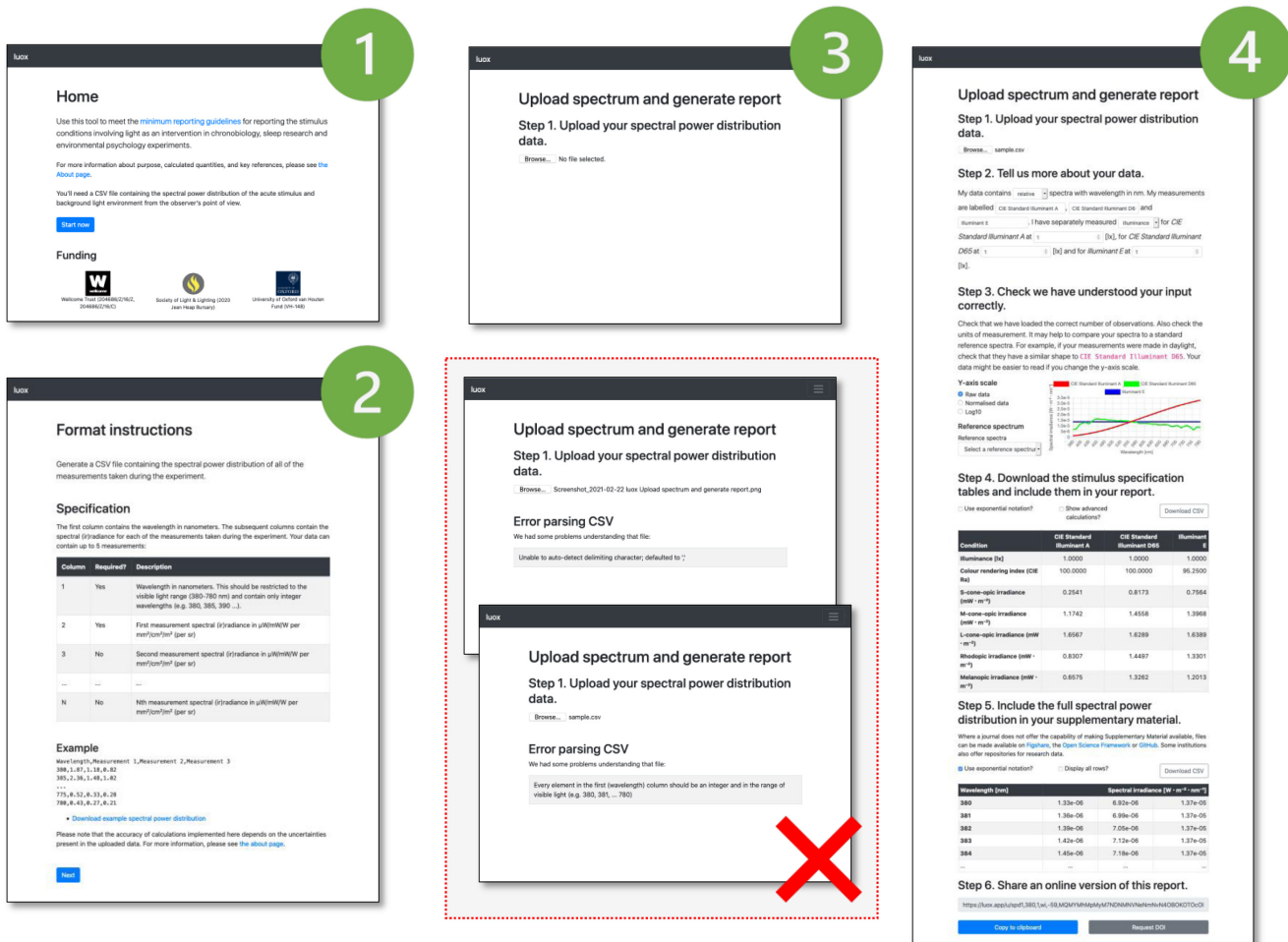


Figure 2. luox graphical user interface. (1) Home and landing page; (2) formatting instructions for spectra to be uploaded; (3) upload dialogue; (X) failure of upload with indicative error messages; (4) report with calculated quantities.

matching experiments by Wright⁶¹ and Guild⁶². The chromaticity coordinates are calculated by weighting the spectrum by the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ colour matching functions, yielding tristimulus coordinates X , Y and Z and then normalising: $x = \frac{X}{X+Y+Z}$ and $y = \frac{Y}{X+Y+Z}$. It is useful to note that CIE 1931 $\bar{y}(\lambda)$ and CIE 1924 $V(\lambda)$ are equivalent.

- **CIE 1964 x_{10}, y_{10} chromaticity (10° observer).** The CIE has also standardised 10° colour matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, and $\bar{z}_{10}(\lambda)$, and associated chromaticity coordinates x_{10} and y_{10} ⁶³. The 10° colour matching functions are based on psychophysical measurements done by Speranskaya⁶⁴ and Stiles and Burch⁶⁵.

α -opic quantities following CIE S 026/E:2018. In 2018, the International Commission on Illumination (CIE, abbreviating the French *Commission Internationale de l'Éclairage*) released the new International Standard CIE S 026/E:2018 (“CIE System for Metrology of Optical Radiation for ipRGC-Influenced

Responses to Light”,⁵⁴), standardising the spectral sensitivities for ipRGC-mediated responses to light, and associated quantities. The spectral sensitivities of the L, M and S cones correspond to those developed by Stockman and colleagues^{66,67} and endorsed by the CIE⁶⁸. The rods’ spectral sensitivity corresponds to the standardised scotopic luminosity function, $V'(\lambda)$ ⁵⁹, based on psychophysical measurements⁶⁹. The melanopsin spectral sensitivity curve in CIE S 026/E:2018 is the same as the one used in the influential Lucas *et al.* article⁷⁰ and associated Irradiance Toolbox (see supplement of 70), based on previous proposals^{71,72}. To make calculations of CIE S 026/E:2018 related quantities accessible, the CIE released an Excel-spreadsheet based toolbox⁵⁵ and associated user guide⁷³.

luox implements the following quantities based on CIE S 026/E:2018:

- **α -opic irradiance [mW/m^2] or radiance [$mW/m^2/sr$].** The α -opic irradiance or radiance of a spectrum is the weighted sum of the spectrum and the α -opic spectral sensitivity. Here and in the definitions for EDI/EDL and ELR below,

“ α -opic” is a placeholder term that can be filled by any of the five photoreceptors, the L, M and S cones, the rods and melanopsin. For example, the spectral irradiance or radiance weighted by the L cone spectral sensitivity is called the L-cone-opic irradiance or radiance, and the spectral irradiance or radiance weighted by the melanopsin spectral sensitivity is called the L-cone-opic irradiance or radiance.

- *α -opic equivalent daylight illuminance (EDI) and luminance (EDL).* The α -opic equivalent daylight illuminance (EDI) or luminance (EDL) calculates the photopic (il)luminance of a standard daylight spectrum (CIE Standard Illuminant D65, corresponding approximately to daylight with a correlated colour temperature of 6500K) that matches the α -opic (ir)radiance. Alternatively stated, the EDI/EDL tells us the (il)luminance that a daylight would have to have to yield the same α -opic (ir)radiance.
- *α -opic efficacy of luminous radiation (ELR).* The α -opic efficacy of luminous radiation is the ratio between the α -opic (ir)radiance and photopic (il)luminance, providing a simple, normalised indicator of the α -opic “content” of a spectrum. The melanopic ELR, i.e. the melanopic efficacy of luminous radiation, is similar to the the M/P ratio method proposed elsewhere⁷⁴.

In addition to linear notation, it is possible to toggle the display to exponential notation. While display of the calculated values is truncated to four decimal digits, the downloaded report, and indeed all underlying calculations, includes the numbers up to floating point precision (double-precision 64-bit binary format IEEE 754).

Encoding of spectral power distributions

Spectral power distributions are typically stored as files in an MS Excel spreadsheet, comma-separated (CSV), XML (e.g. 75), JSON or other schema-based formats (e.g. 76). Storage of files requires an infrastructure, e.g., a server. To lose this requirement and enable the sharing of spectral power distribution data without sharing files, we (M.H.) developed a library with no external dependencies called *spdurl* written in JavaScript. *spdurl* encodes a spectral power distribution in a URL accurately and concisely. While the RFC for URLs (RFC 2616⁷⁷) does not specify an upper length limit, many web browsers may truncate it to 2 kB, which we pragmatically adopt as the limit for URLs here.

spdurl exploits the following aspects of spectral distributions:

- *Wavelength sampling:* Wavelengths are assumed to be uniformly spaced, allowing us to write only the first value and an increment, with the total number of samples implicit in the number of samples given. Some spectroradiometers produce nonuniform wavelength spacing, so we expect these users to resample to a uniform spacing, as with the rest of *luox*.
- *Compression:* We compress the spectra using a scheme that encodes spectral bands in two URL-safe bytes each, across a variety of units. The measurement process within CCD spectrometers uses a shared shutter for all elements in the array, allowing us to share an exponent for all values. This is also often done in HDR formats, like Radiance RGBE⁷⁸. As a

base for our shared exponent, we chose $\sqrt[2]{2}$, sacrificing 1/8 bit to quantisation, rather than 1/2 bit if we had used 2 as a base. We do not constrain the exponent value (large exponents just use more bytes), so extremely small and large values can be represented, but most exponents use one or two bytes. In this way, energy can be stored as a linear value even at very small irradiances without worrying about range limits. While the best available CCD spectrometer arrays are specified to measure 16 linear bits, real-life signal to noise is much lower. We began with an 18-bit mantissa, but subsequently determined that for most uses, 12 bits of gamma-encoded data were sufficient for our calculations. To balance the accuracy of smaller and larger values, we informally determined that $\gamma = 2.0$ gave lower error than linear or cubic encodings. We perform rounding to 12 bits to avoid quantisation bias, which may result in small changes in the spectrum and derived quantities.

- *String encoding:* We encode the resulting string as a URL-safe base64 (RFC 4648⁷⁹), meaning that each 12-bit value can be written using two bytes, with no padding.
- *Spectral resolution limits:* Since we use two bytes per value, this means that visible spectra can be encoded in a valid URL (2kB) down to about 0.5 nm spacing. Meters that have high spectral resolution may wish to resample to fewer values before encoding.
- *Spectral units:* We use a dictionary of datatypes (30 to date), which can represent spectral quantities (so that “/nm” is common to all) using just 2-3 bytes. For instance, the shorthand “uwi” is used to represent “uW/cm²/nm”. Additionally, action spectra, transmittance, radiance, and quantal units are available using similar short abbreviation given in the software. Many file formats assume the reader knows the units in use; in *spdurl*, we make no such assumption, and so, this field is required.
- *Meta-data specification:* Measurement conditions, like time zone, date, location, and user-specified name are allowed as optional metadata, when there is space at the end.

As an example, our library can encode a spectral radiance distribution specified between 380 and 780 nm with 1 nm spacing using 804 bytes, and a 10 nm sample (36 bands) from an X-Rite meter can occupy only 90 bytes, as succinct as the following:

```
spd1,380,10,wi,4,uJuJuI4m68488W_h-38t7c6S6J5
A3i4M4G4G3N1u0Hx-w0v0uwuFtmr-qsp2ohncrB-
vsxz2j
```

spdurl-encoded spectral power distributions can be shared across platforms, e.g., in *luox*:

```
https://luox.app/u/spd1,380,10,wi,4,uJuJuI4m68488W
_h-38t7c6S6J5A3i4M4G4G3N1u0Hx-w0v0uwuFtmr-
qsp2ohncrBvsxz2j,nMeasurement%201
```

and in *fluxometer*:

```
https://fluxometer.com/rainbow/#!id=data/spd1,380,10,u
wi,4,uJuJuI4m68488W_h-38t7c6S6J5A3i4M4G4G3N1
u0Hx-w0v0uwuFtmr-qsp2ohncrBvsxz2j
```

spdurl (RRID: SCR_020992) is written in JavaScript for use on the web and node.js servers. It is available under the MIT License (code base at [Github](#), npm package [here](#)). *spdurl* can be used as a standalone package independent of *luox*, and we hope that it will be attractive to other users.

Requesting DOIs

To facilitate the sharing of URLs encoded in *luox*, we offer the deposition of encoded URLs in the [Oxford Research Archive](#). Users need to complete a form with minimal information, and upon manual approval, a DOI will be assigned.

Reference spectra

luox allows for graphical comparisons of uploaded spectra with a series of CIE reference spectra. These include Standard Illuminant A, Standard Illuminant D65, and Illuminants C, D50, D75, F1 through F12, FL3.1 through 3.15, HP1 through HP5, LED-B1 through LED-B5, and LED-BH1, LED-RGB1, LED-V1, LED-V2⁸⁰.

Validation and CIE endorsement

luox has been validated by the CIE. The “black-box validation”, using 43 spectra from various sources (19 at 5 nm and 24 at 1 nm), confirmed that the calculations performed by *luox* was within defined tolerance intervals. The CIE report states⁸¹:

“This software incorporates methods, formulae, spectral function calculations and spectra from the International Commission on Illumination (CIE). The CIE endorses this software having made a black-box evaluation of the software as of Feb. 11, 2021, finding that the software performs satisfactorily. This software is not a replacement for the CIE publications

and works from which it is derived. The user is advised to consult the original publications and works for proper understanding of and calculation of the result of this software.”

Discussion

Here, we present the *luox* platform for facilitating and sharing calculations of physiologically relevant quantities related to light and lighting. *luox* is open-access and open-source. *luox* is fully functional and modular, enabling the incorporation of other spectrally derived quantities in the future.

Data availability

No data are associated with this article.

Software availability

Software available from: <https://luox.app/>

Source code available from: <https://github.com/luox-app/luox>

Archive source code at time of publication: <https://doi.org/10.5281/zenodo.4594093>⁵⁶

License: GPL-3.0

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This is a well-written report from an experienced group of researchers. Their report describes a free, open source, and open access platform to calculate quantities and metrics to describe the ability of optical radiation to stimulate each of the five (α -opic) photoreceptor types in the human eye. Each photoreceptor potentially can contribute, via the melanopsin-containing intrinsically-photosensitive retinal ganglion cells (ipRGCs), to neuroendocrine, neurobehavioral and circadian effects of light in humans. Alongside these values, the tool provides commonly used colorimetric calculations. The International Standard CIE S 026:2018 defines spectral sensitivity functions, quantities and metrics in units of α -opic quantities that are compliant with the International System of Units (SI) and currently recommended by the CIE to report values in research studies and lighting applications relevant to the physiological effects of light. A parsimonious exploration of three spectra was entered into the platform: a monochromatic light source, a polychromatic white LED light source and a polychromatic incandescent light source. The resulting data were identical to those provided by the CIE excel toolbox. We were very impressed with the platform's abilities and ease-of-use. Finally, having the data encoded into an HTML link is brilliant and further allows easy sharing of data among laboratories and individuals. In summary, *luox* provides researchers and other professionals who desire to know the potential neuroendocrine, neurobehavioral and circadian effects of a light source a useful tool for quantifying light for these physiological effects.

Is the rationale for developing the new software tool clearly explained?

Yes

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Yes

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?

Yes

Are the conclusions about the tool and its performance adequately supported by the findings presented in the article?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Photobiology

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 09 April 2021

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Timothy Brown

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This report describes a new open source web-platform for calculating various quantities relating to light and lighting as experienced by a standard human observer. In particular, the tool facilitates calculations of metrics related to ipRGC-influenced responses to light as described in the CIE S026 international standard, as well as additional colorimetric calculations.

There is growing appreciation that 'non-visual' effects of light can influence health and well being (e.g. via effects on the circadian system and sleep) and substantial interest in harnessing such effects for practical benefit. This tool is potentially of great utility in facilitating appropriate quantification and description of lighting conditions for scientific studies and in real-world applications. The tool also provides a simple means by which such information can be shared and referenced.

Given that the tool is OS-independent and does not require any proprietary software this should be of great utility across the spectrum from vision/circadian scientists to lighting professionals.

The report does not seem to directly describe cross-validation of the outputs of the web platform with existing tools (e.g. the CIE excel tool). I do not doubt the outputs of both tools are the same (and imagine the Authors have confirmed as much) but direct confirmation that this is the case would be worth including.

Is the rationale for developing the new software tool clearly explained?

Yes

Is the description of the software tool technically sound?

Yes

Are sufficient details of the code, methods and analysis (if applicable) provided to allow replication of the software development and its use by others?

Yes

Is sufficient information provided to allow interpretation of the expected output datasets and any results generated using the tool?

Yes

Are the conclusions about the tool and its performance adequately supported by the findings presented in the article?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: circadian and visual neuroscience

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 30 Apr 2021

Manuel Spitschan, University of Oxford, Oxford, UK

Thank you for your review. The cross-validation of the outputs is currently being performed by the CIE and will be written up as a report, which will be included on the website.

Competing Interests: No competing interests were disclosed.