Towards a wearable sensor for spectrally-resolved personal light monitoring

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Abstract. Given the large impact that the spectrum and intensity of light can have on people's health and well-being, it is of fundamental importance to understand the properties of light received under normal living conditions. Historically, as research into the biological responses of light has traditionally focused on laboratory studies with controlled lighting conditions, little is known about people's light exposure outside of experimental environments. *Spectrace* is the first wearable compressive spectrometer designed for continuous spectral light tracking in everyday environments. This paper presents the sensor and its evaluation based on wearability considerations and three performance criteria: 1) its accuracy (in terms of spectral sensing capability), 2) its reliability (notably as far as directional response is concerned), and 3) its adaptability to the large dynamics of ambient conditions. Results show the potential use of the newly developed sensor for chronobiological studies and beyond.

1. Introduction

Within the last century, people's relationship with their lighting environment has dramatically changed. Electric lighting especially late-night screen time is the new normal, untethering activity from the solar path. This relatively recent decoupling between evolutionary *zeitgebers* (external cues that entrain or synchronize an organism's biological rhythms) and wake activity can conceptually be seen as a generalized, uncontrolled experiment resulting from the Great Acceleration. Over the last couple decades, investigations have been conducted to study the effects of this decoupling and, more generally, of light exposure on human biological responses, given the large impact that light can have on people's health and well-being (e.g., combat workplace fatigue, enhance sleep quality, increase alertness, boost immune system) [1–3]. Since the discovery of intrinsically photosensitive (melanopsin-containing) retinal ganglion cells (ipRGCs) twenty years ago [4, 5], extensive research in the field of chronobiology has been conducted on this topic. However, considering that research into the biological responses of light has traditionally focused on laboratory studies with highly controlled lighting conditions, little is known about people's light exposure outside of experimental environments. The diversity of light exposure profiles in the greater population (i.e., the variety of exposure patterns to different light sources, including daylight), or their frequency of occurrence in daily life, are mostly unknown. Without knowledge of these so-called *spectral diets* [6] of contemporary humans, we are unable to assess the potential impact of light on health and well-being. The lack of large-scale light exposure datasets is due in part to technological barriers summarized by restrictions on size, weight, power, and cost (SWaP-C) on existing hardware, especially when spectral resolution is sought as the effects of light on human biology are known to depend on spectral irradiance [7, 8]. While a number of low-fidelity light-logging actigraphy dosimeters (based on tristimulus signals) have been proposed over the years in the hopes of increasing in-field viability, they have been tested repeatedly in the literature with mixed results [9–13]. Although these devices seek to mimic the physiological and neurophotic responses, our understanding of the physiology and neurodynamics is still incomplete. This eagerness to create *the* dosimeter has led to contentious debate within the chronobiology community [14].

This paper introduces and evaluates *Spectrace*, a wearable spectrometer developed to enable accurate energy-based measurements of individual light exposure. The newly developed device aims at solving technological and design issues and offers a high degree of wearability thanks to a multi-disciplinary approach including industrial designers. In the following, the considerations and innovations made in hardware and software are outlined and an evaluation of the sensor is carried out based on wearability considerations as well as three performance criteria: (1) the accuracy of the sensor's spectral response (spectral sensing capability), (2) the reliability of its directional response (signal fidelity and field of view), and (3) the adaptability of its dynamic range to ambient conditions.

2. The Spectrace device

2.1.1. Conceptual system design

Spectroradiometry is the practice of measuring the amplitude and wavelength of light in the energy-related, *radiometric*, units of irradiance (Watt/cm^2). Beyond the debate on what exactly constitutes "spectral" resolution, we can broadly characterize devices into three classes: (1) tristimulus, (2) multispectral 4-10 channels, and (3) hyperspectral 11+ channels [15]. Modern state-of-the-art spectroradiometers operate at the high-end of the hyperspectral range with as many as 2048 channels and use a diffraction grating to first split then focus the light, with a lens, onto a detector. This process requires high-precision components that are expensive and bulky. Such devices are not wearable and typically require specialized software for data access and analysis. In contrast, recent advances in complementary metal oxide semiconductor (CMOS) fabrication have enabled integrated filter-array spectrometers that can sample in the low hyperspectral regime (11–18 channels spaced evenly over the visible range) [16]. While other technologies exist in the middle of the hyperspectral range, the main trade-offs in assessing the viability of the technology occur around 20 channels due to the SWaP-C optimality of "single shot" CMOS filter-array sensors.

In contrast to designing *physiomimetic* hardware that exploits physiological regularities, we focused on exploiting regularities in the spectral domain to recover spectral irradiance data from existing low-fidelity imaging hardware. We suppose that most of the information collected by mid, and high range hyperspectral sensors, is redundant. In the case of *Spectrace*, only 14 points are sampled across the visual domain (d_m = 14) constituting a spectral 'fingerprint'. Our spectral reconstruction algorithm (SpecRA$^{\text{TM}}$) then converts this low-dimensional representation to a target high dimensional signal with 81 points over the same frequency range. Unlike interpolative methods, SpecRA$^{\text{TM}}$ relies on a concepts related to *compressive sensing* and data-driven sparse sensor placement [17] whereby signals can be recovered by exploiting regularities in a low-rank feature space. Practically, this involves regressing on a library of n spectra in a $d_w \times n$ matrix Ψ where $d_w = 81$ is the target 'working' dimension. Since our library comprises real signals, we can fill in the missing information by making informed guesses as to the type of signal that is most likely to generate the fingerprint captured by our device. We illustrate how spectra of variable complexity can be approximated by other signals even when the library does not contain a close match (Figure 1). The proposed approach is more "future proof" in the sense that it is indifferent to the details in the spectra collected and can thereby enable different interpretations of the data as our knowledge of the neurophotic effects continues to evolve [15]. Furthermore, our method is generalizable to other frequency domains and allows for the derivation of other metrics outside human biology (e.g., photosynthetic photon flux).

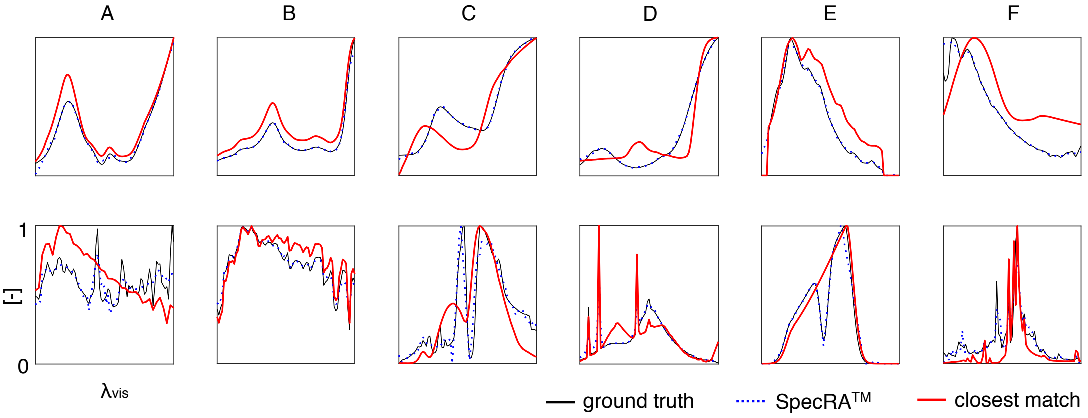

Figure 1. Ground truth and reconstructed spectra for signals with low (top) and high (bottom) complexity. The closest match refers to the signal in the library Ψ with the lowest mismatch error with the ground truth signal. Interestingly, SpecRA™ finds missing signal details below the Nyquist rate.

2.1.1. *Hardware and case design*

Figure 2 illustrates the hardware and case design of the sensor. The device is designed to be worn as a clip (with the use of the magnet) or as a necklace. The diffuse case material allows the light to be transmitted and focused onto the sensor. Secondary and tertiary photodiodes are used to adjust the sensitivity response of the sensor. An accelerometer and gyroscope coupled with an ancillary photopic illuminance sensor provide feedback on the stability of the current light exposure and appropriately modulate the gain affecting the spectral sensors. In this way, we take an energy efficient approach to data collection by adjusting temporal sampling frequency based on changes in the environment

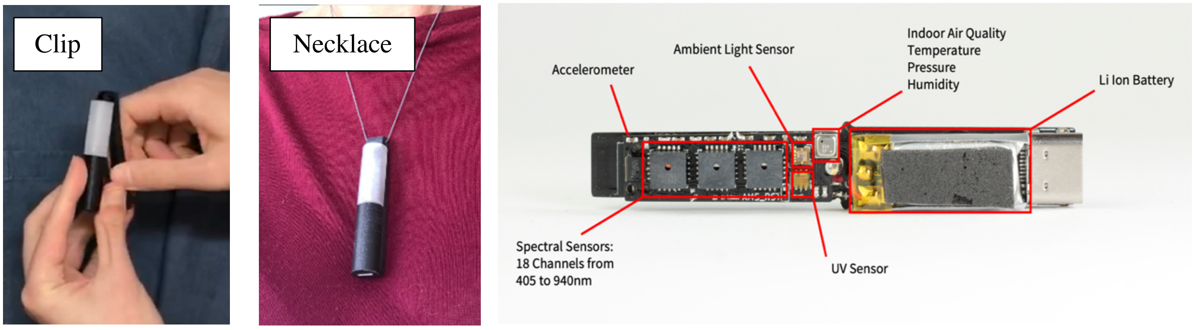

Figure 2. Spectrace device components, and wearability options. N.B.: indoor air quality, temperature, pressure, and humidity sensors in the device are not discussed in the present work and are the subject of ongoing hardware modifications for subsequent versions.

3. Sensor evaluations

3.1. *Performance criteria*

In order to evaluate the performance of the device based on three performance criteria (i.e., spectral response, directional response and dynamic response), ad hoc laboratory experiments were conducted in a dark chamber. For spectral testing, results were compared to a state-of-the-art spectrometer for monochromatic and polychromatic light sources. Directionality was tested using a spotlight on a hemispherical track in steps of 5 degrees. Dynamic resolution and dynamic range/linearity were tested in an integrating sphere with a dimmable polychromatic light source.

3.1.1. Spectral response

While the hardware contained within *Spectrace* limits the resolution of the output to 14 irradiance points sampled between 380 and 780 nm, the reconstruction software SpecRA^{TM} outputs a 81-by-1 normalized spectrum that can be compared against the ground truth. Towards this end, we evaluate the spectral response by measuring a diversity of spectra (broadband and narrowband) and report the proportion of reconstructed signals within a target error margin. Here the error is defined as the root mean square error (RMSE) between the output and ground truth signal measured with a state-of-the-art spectroradiometer. In Figure 3 we show that SpecRA^{TM} works in two regimes: finding the best fit match in our pre-complied library when it exists and reconstructing an unknown signal from combinations of signals in the library when there is not a close match. Figure 3 further shows that SpecRA^{TM} recovered 82% of signals within the target error margin with a group mean of 0.02 ± 0.01 and was able to recover 35% of signals even when there were no close matches in the training set with 99% of signals either within the error margin or at a lower mismatch error than their closest match.

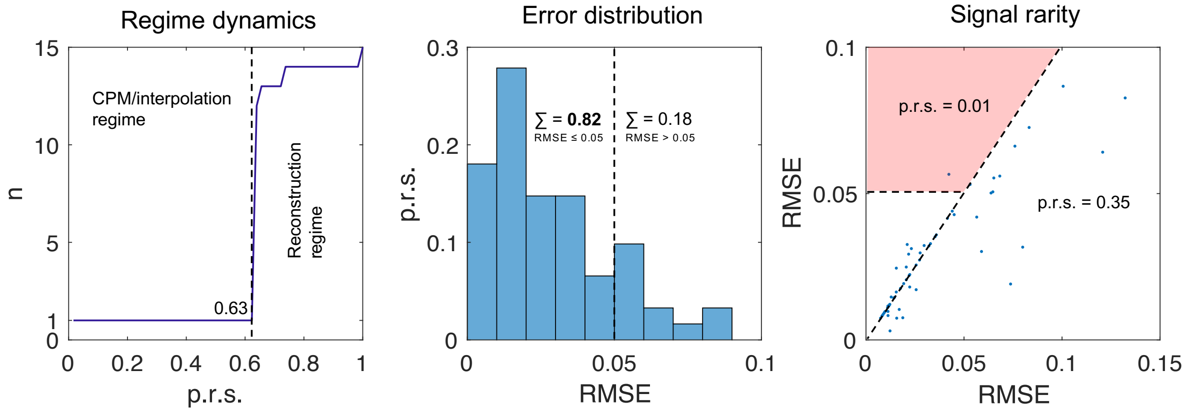

Figure 3. Spectral response test results. p.r.s. = *proportion of reconstructed signals*.

3.1.2. Directional response

The directional response of the sensor is evaluated by the deviation of the measured response to the cosine response, as expressed by Equation (1). Since light scatters off impurities embedded in the case material, some light from shallow angles is directed onto the sensor. However, because the sensor response may need a minimal density of photons to induce a current, the addition of impurities can hinder the sensor's ability to recover spectral information in dim light conditions. This can be accounted for (to an extent) by adding a signal amplifier. Because the optical properties are hardcoded into the design of the sensor, we ensure that there is enough flexibility in gain to account for the limitations in the trade-off in the material choice.

$$\mathrm{f}_2 = \int_0^{\epsilon_{\max}} \left| \frac{\mathrm{Y}(\epsilon)}{\mathrm{Y}(\epsilon = 0)\cos\epsilon} - 1 \right| \sin 2\epsilon \, \mathrm{d}\epsilon \tag{1}$$

where $\mathrm{Y}(\epsilon)$ is the measured illuminance from a collimated light source mounted inside of a hemispherical dome at an angle ϵ. We were able to measure f_2 directly using a LMT pocket lux 2 as reference. The result of $f_2 = 2.07$ % put *Spectrace* in class "A" [13] for planar illuminance (Figure 4). Of course, directionality from a user perspective is influenced by wearability. We found that chest-worn devices are only rarely poor proxies for face-plane irradiance as most daily environments facilitate exposures that are comparable when measured on the chest or at the eye and that short fluctuations in movement have a negligible impact due to averaging of exposures over time as observed both in the sensor hardware and in human biology.

3.1.3. Dynamic response

With respect to dynamic *range*, we want to check that variation in the intensity of the light source (input) increases linearly with current (output). The CIE recommends using a *dynamic mismatch factor* defined in Equation 2:

$$f_3(Y) = \frac{Y(X)}{Y(X_{\max})}\frac{X_{\max}}{X} - 1 \tag{2}$$

where Y(X) is the measured Spectrace illuminance at a reference illuminance X; ideally Y(X) = X. We measured the linearity index under a diffuse polychromatic source for 2700K and 6500K and found $f_{3,\max} = 0.8$ and $f_{3,max} = 9.4$ respectively (Figure 4).

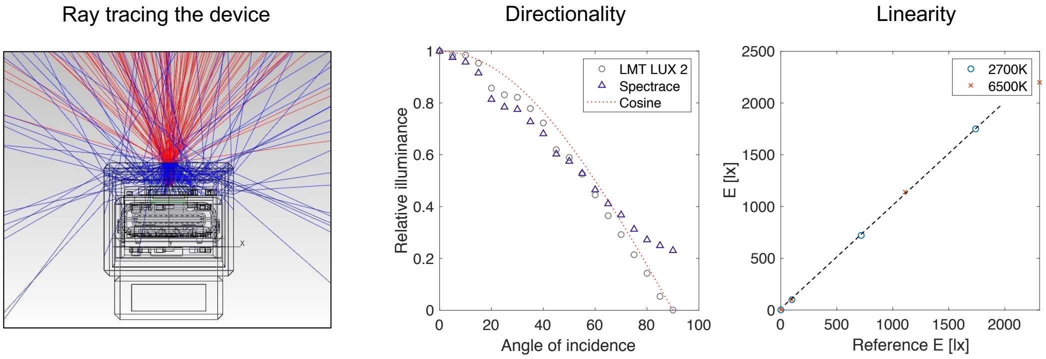

Figure 4. Results from the ray tracing simulation, f_2 (directionality), and f_3 (linearity) metrics.

3.2. Wearability

Wearability considerations for light-logging actigraphy dosimeters are necessary to ensure high compliance by creating a positive experience for the user. We tested the wearability of our device by conducting a trial test with 20 early adopters. Each was asked to wear the sensor as a necklace or as a clip for up to 3 weeks and to respond to a questionnaire. The results of the wearability survey indicate that the sensor was preferably worn as a clip, and that extension of the 24hr battery life would increase usability. Importantly, the survey revealed that the current shape and weight did not hinder participants' daily activities nor made them feel uncomfortable. Table 1 summarizes the results of the wearability survey, highlighting that one problem of the current design is that users tended to forget about it when changing clothes. This issue is currently being addressed in the new design developments.

Table 1. Summary of wearability survey.

	Yes, once	Yes, 1-3 times	Yes, > 3 times	No
Did you (temporarily) lose Spectrace?	13.3%	20.0%	6.7%	**60.0%**
Did you forget to wear Spectrace at the beginning of your day?	20.0%	**53.3%**	20.0%	6.7%
Did you forget to remove Spectrace at the end of your day?	0.0%	20.0%	0.0%	**80.0%**
Did you forget to move Spectrace when changing clothes (e.g., putting on/removing a jacket, changing into sport clothes)	8.3%	**50.0%**	33.3%	8.3%
Did you forget to charge Spectrace at the end of your day?	13.3%	33.3%	6.7%)	**46.7%**
Did you (temporary) remove Spectrace during the day?	6.7%	26.7%	6.7%	**60.0%**

4. Conclusion

We have introduced *Spectrace*, a wearable sensor for spectrally-resolved personal light monitoring. Our tests for the three performance criteria illustrate that *Spectrace* can recover a diversity of spectra at different bandwidths. Measurements of intensity as a function of angle of incidence demonstrated a near-cosine response. Dynamic responses did not result in distortion of the spectrum. Wearability investigations prompted new design developments. Despite the motivation to develop a spectrally-resolved sensor came from the need for robust light tracking in chronobiological studies, the applications of *Spectrace* are unconstrained. Towards this end, we hope *Spectrace* can be integrated across disciplines as a convenient tool for researchers, healthcare professionals, and even the general public.

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