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REAL-LIFE CHARACTERIZATION OF EYE EXPOSURE TO LIGHT USING A NEW INSTRUMENTED EYEWEAR: A PROOF-OF-CONCEPT STUDY

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Abstract

New and convenient devices for continuously monitoring eye light exposure levels in real life are needed to address current knowledge gaps. This two-week study, involving 10 participants, assessed the real-life reliability and usability of a device developed to meet this need: newly instrumented eyewear containing four calibrated sensors (an illuminance ambient light sensor, an irradiance spectrometer with eight channels, and two proximity sensors). The eyewear provided reliable, objective data on light dose and spectral composition, and enabled analyses according to time of day, light environment (indoor/outdoor; different light sources), and weather conditions. Feedback on aesthetics, comfort, and usability was positive. These data support the larger-scale use of this new instrumented eyewear in future studies involving real-life characterization.

Keywords: e.g.: light exposure, wearable, light, sensors

1 Introduction

Light is essential for vision but can also cause irreversible damage to the visual system due to genetic and environmental factors, leading to conditions such as cataracts, glaucoma, and photokeratitis. Beyond vision, light influences physiological and neuroendocrine functions, including circadian rhythms by modulating melatonin and cortisol production cycles (Buch and Hammond, 2020). The effects of light vary based on its amount and wavelength specificity, impacting human health differently. For instance, exposure to blue light and high-energy light in the blue-violet spectrum is a risk factor for age-related macular degeneration (Arnault et al, 2013), and cumulative retinal damage is often irreversible (Marie et al., 2020). Blue light also affects sleep quality and circadian rhythms (Ishizawa et al., 2021).

Given the significant impact of light exposure on health, it is crucial to develop tools for objective measurement of the light environment, including spectrum characterization, rather than relying solely on subjective assessments like questionnaires (Alvarez et al., 2013). Wearable light measurement devices, such as bracelets, have been developed to collect real-world data on light exposure. However, these devices must measure light closest to the eye (Aarts et al., 2017), near the corneal plane, and be easily integrated into daily life. Many existing devices fail to meet these criteria, either being inconvenient or not discrete enough for everyday use.

The Clouclip device (Wen et al., 2019), which attaches to glasses frames, measures light exposure at eye level but has limitations such as large size, inability to analyze spectral light components, and reliance on cloud platforms outside Europe for data analysis. Therefore, new devices are needed to continuously monitor indoor and outdoor spectral light exposure at the closest level to the eye cornea, integrating conveniently into daily life (Münch et al., 2020).

The Luca project (Gourraud et al., 2024) addresses these issues by incorporating a unique combination of sensors, including an 8-channel spectrometer, into an eyeglass frame. The device is designed for all-day wear and nightly charging. This proof-of-concept study aimed to test the Luca eyeglasses in real-life conditions, assessing their ability to collect consistent and usable data on the light environment and evaluating participant feedback on comfort and usability.

2 Methods

2.1 Study design

This observational study tested the Luca new instrumented eyewear (Figure 1) over two weeks, from March, 15 to April, 21, 2021. Participants had to be ametropic and remain within the laboratory area near Paris, France. The study was conducted in accordance with the general principles of the Declaration of Helsinki and all applicable laws and regulations concerning human studies, with informed consent obtained from all subjects. The functionality of the new eyewear in real-life conditions was assessed based on the ability of its sensors to provide usable and consistent data on the light environments to which the participants were exposed throughout the study.

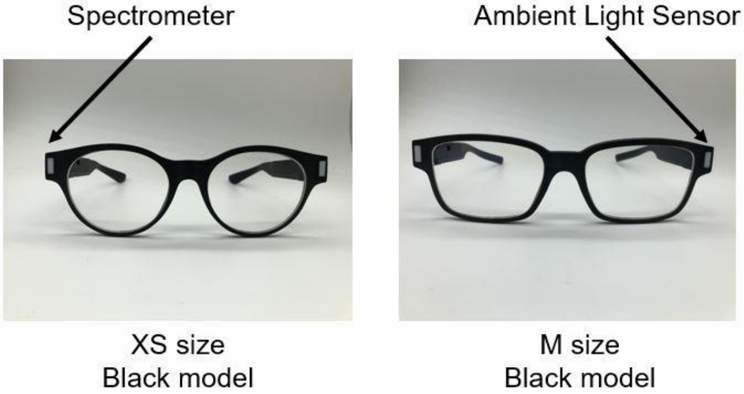

Figure 1 – The two designs of the Luca instrumented eyewear equipped with two light sensors

Four visits were conducted: inclusion, pre-visit, initiation, and end-of-study. During the inclusion visit, participants selected an eyewear model and provided prescriptions for personalised lenses. The pre-visit ensured proper visual acuity, and the initiation visit involved the collection of equipment and reminders about the study protocol. The participants also responded to a first questionnaire evaluating global aesthetics, comfort, size, weight, and field of vision, rated using a numeric rating scale (NRS) ranging from 1 (not satisfied at all) to 5 (very satisfied). During the test, participants received daily email reminders to recharge their glasses and complete light history questionnaires based on the Harvard Light Exposure Assessment questionnaire (Bajaj et al., 2011). At the end of the study, participants returned the instrumented eyewear and completed final questionnaires on aesthetics, comfort, and usability using an NRS ranging from 1 (not satisfied at all) to 5 (very satisfied). Participants could also leave a free comment for each item. If applicable, participants were also asked to give the reason why they had not worn the Luca eyewear at certain times of the day.

2.2 Newly instrumented eyewear

The Luca instrumented eyewear (Gourraud et al., 2024) is equipped with four calibrated sensors: an Ambient Light Sensor (ALS), a spectrometer with eight channels (Table 1), and two proximity sensors.

Table 1 – Characteristics of the 8 spectral channels of the spectrometer

	Chan0	Chan1	Chan2	Chan3	Chan4	Chan5	Chan6	Chan7
Type of light	purple	blue-indigo	blue-turquoise	green	yellow-green	yellow/amber	orange	red
Lower limit (nm)	400	432	460	497	535	575	610	652
Peak (nm)	417	452	480	515	552	592	635	675
Upper limit (nm)	432	465	498	536	575	615	655	704

The light sensors, placed under diffusing optical windows, measure illuminance and irradiance. Several in-lab tests confirmed their linearity, dynamic response, angular response and photopic sensitivity. The whole system has been designed to guarantee the spatial sensitivity of a Lambertian profile oriented along the axis of the face, while ensuring low signal attenuation to remain within the optimal operating range of the sensors. They have been characterized both when integrated into the frame and when not integrated to ensure a proper calibration. They showed no sign of saturation, up to 100 000 lux, the maximum level of light emitted by the solar source. The proximity sensors could provide information on whether the eyewear was worn on the head. Data were collected by the sensors every 30 seconds, except when the eyewears were charging (data were collected every 30 minutes in this case).

2.3 Data processing and analyses

After the study, the instrumented eyewears were connected to a custom-made software for data extraction and analysis. Data from nine Luca eyewears were analyzed, collecting 263 263 data points over 2 193 hours. Technical issues excluded one participant's data. Data collection varied due to wear duration of the participant and battery issues. A total of 159 657 data points were used for light exposure analysis, with 118 318 points for light environment analysis. Significantly less data were collected outdoors compared to indoors.

Analyses were performed using sensor data (irradiances in $\mu W{\cdot}cm^{-2}$ from the 8 channels of the mini-spectrometer and illuminance in lux from the ALS). Total irradiance ranging from 400 nm to 704 nm was calculated by summing the values from the eight channels of the spectrometer, and light doses were calculated using both wearing time and irradiances. Responses to the light history questionnaires were analysed, excluding ambiguous or non-wear periods.

3 Results

3.1 Light exposure of the participants

Most data from the spectrometer and ALS showed low irradiance and illuminance levels, with median daily illuminance between 50 and 700 lux. Notably, 55% of values were below 100 lux. Participants spent a median of 77 minutes daily at illuminances >1 000 lux, and 7 minutes weekly above 10 000 lux (Figure 2).

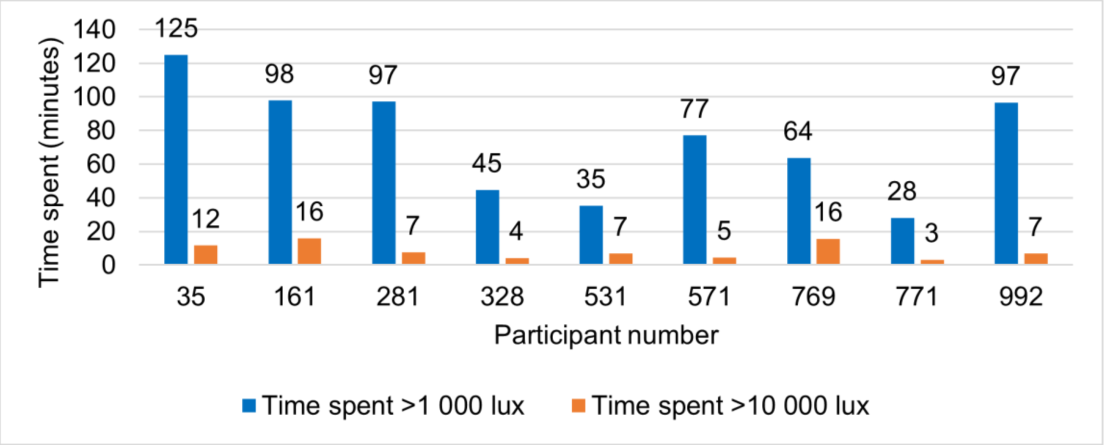

Figure 2 – Mean daily time spent above a given illuminance threshold for each participant over the whole test period while they were wearing the eyewear

The mean daily light dose was 12,45 J·cm^{-2} (min-max: 8,70-112,10 J·cm^{-2}), peaking on sunny days. The highest mean daily light doses were observed on Sunday, April 4th, which was a non-working day during which the weather was sunny. According to their answers to the light history questionnaire, participants spent 13,5% to 28,7% of their time outdoors while wearing the Luca eyewear. The light dose received outdoors varied greatly among the participants, representing 7% to almost 70% of the total dose of light received during the test period.

Analysis of the hour-by-hour irradiance (Figure 3) provided by each channel of the spectrometer showed a rapid increase between 7 am - 8 am and 8 am - 9 am corresponding to sunrise, two peaks at 12 am - 1 pm and at 5 pm - 6 pm relating to lunch time and the end of the working day, respectively, and a sharp decrease between 6 pm - 7 pm and 11 pm corresponding to sunset. Detailed analysis of the light composition revealed that exposure to light with longer wavelengths (yellow-green to red, corresponding to wavelengths between 535 nm to 704 nm) predominated over exposure to light with shorter wavelengths, and in particular over blue light, during hours without sunlight. The largest variations in the level of exposure throughout the day were observed for orange light (610 nm - 655 nm), which was the channel with the highest irradiance.

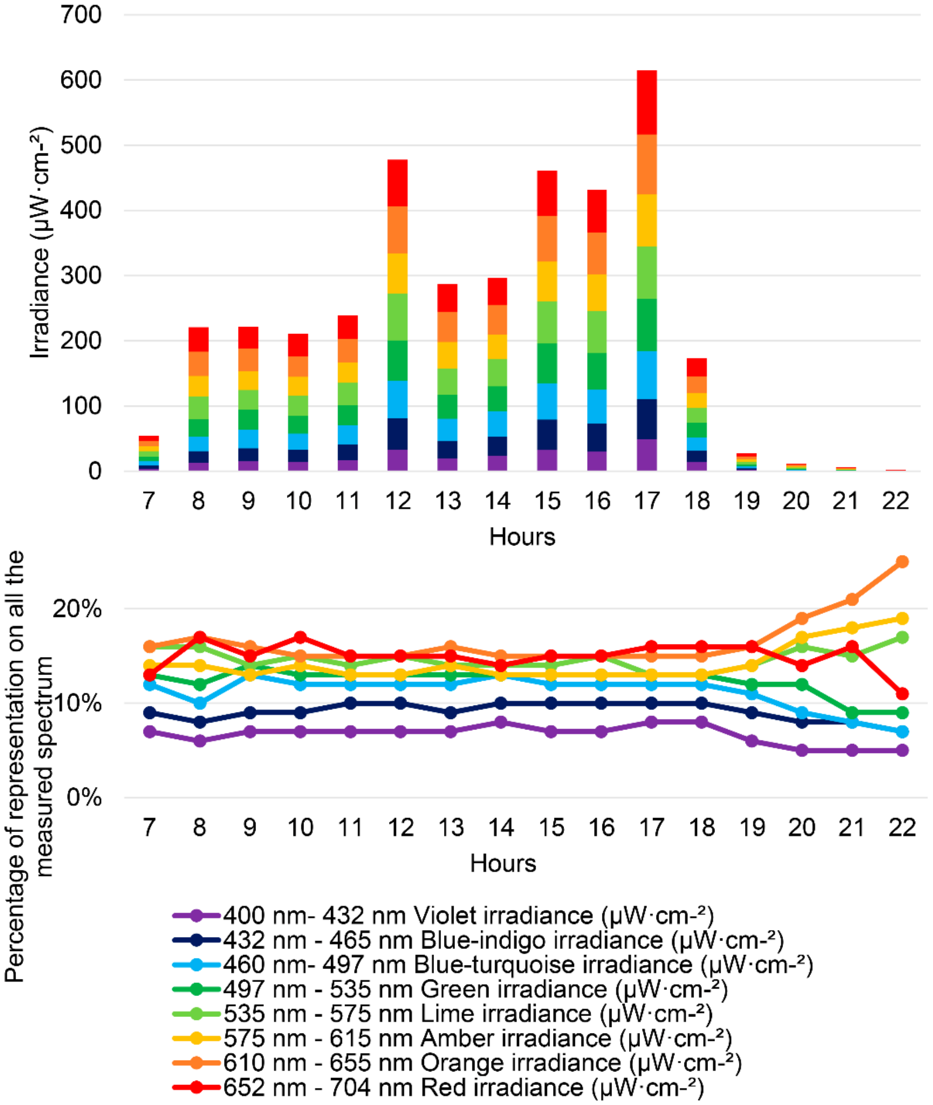

Figure 3 – Composition of the light spectrum throughout the day when the Luca eyewears were being worn for an extended period of time, i.e., from 7 AM to 11 PM.

Focusing on blue light, the mean total of blue irradiance (400 nm - 498 nm) was highest (180 µW·cm^{-2}) between 5 pm and 6 pm (i.e., at the end of the working day), and was also high at 12 am to 1 pm (i.e., during the lunch hour) and at 3 pm to 4 pm. The level of blue irradiance was six times lower at 6 pm to 7 pm compared to at 5 pm to 6 pm, and was very low from 7 pm onwards (after sunset). Hour-by-hour exposure to blue-violet light (here measured between 400 nm and 452 nm) and blue-turquoise light (here measured between 460 nm and 498 nm) irradiance varied greatly and followed the same trend. The levels of exposure to measured blue-violet and blue-turquoise irradiances in the middle of the day were about two times higher than in the morning, about 27,5 times higher than in the evening, and about 106 times higher than at night (Table 2).

Table 2 – Mean irradiance of blue-violet, blue-turquoise, and total blue light normalized over an hour for different times of the day.

	Morning (7 am-10 am)	Middle of the day (10 am-6 pm)	Evening (6 pm -10 pm)	Night (10 pm -7 am)
Blue-violet (400-452 nm) irradiance (μW·cm^{-2})	24,44	51,48	1,8	0,49
Blue-turquoise (460 - 498 nm) irradiance (μW·cm^{-2})	25.93	47,24	1,73	0,44
Blue total (400 - 498 nm) irradiance (μW·cm^{-2})	60.23	119.26	4,3	1,16

3.2 Light environments

According to the daily light history questionnaire, the lowest illuminance and irradiance levels were recorded indoors with only artificial light. Indoor levels were seven times higher when natural light was present (Figure 4). Outdoors, light levels were five to six times higher in open landscapes compared to urban areas.

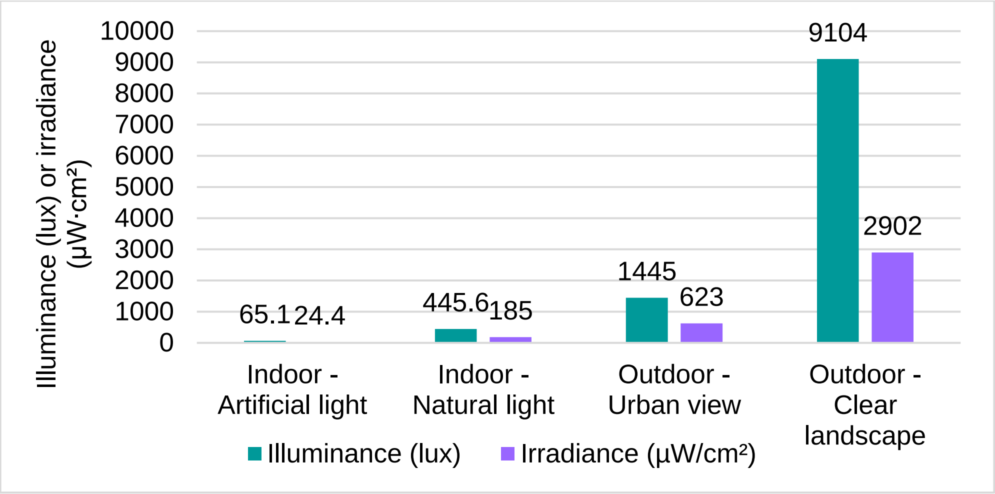

Figure 4 – Mean illuminance and irradiance according to the different lighting environments

In indoor environments with artificial light, irradiance was low (<4 μW·cm^2), with yellow to red light dominating (Figure 5).The light with longer wavelengths, especially amber to red light (595 nm to 704 nm), represented about 50% of the total irradiance, and the blue light forms (400 nm to 498 nm) represented <25% of the total irradiance. Irradiance values collected indoors with natural light were about 10 times higher than those collected indoors with artificial light, ranging from 12 to 28 μW·cm^{-2}, depending on the channel. The proportion of the total blue light (400 nm and 498 nm) was >25% of the total irradiance (measured blue-violet = 11,6% and measured blue-turquoise = 12%), and the proportion of irradiance from light with longer wavelengths was lower than in indoor situations with artificial lighting only. When the participants were outdoors in open spaces, the irradiance values for each channel were respectively about 10 times and 100 times higher than those collected indoors with natural light and indoors with artificial light only. The proportion of total blue light was also higher when the participants were in open spaces, at the expense of light with longer wavelengths, especially amber (595 nm to 615 nm).

When the participants were outdoors in urban areas, the irradiance values for each channel were between 48 and 97 $\mu W \cdot cm^{-2}$, which was almost four times higher than the values observed indoors with natural light and 3,5 times lower than those observed in open spaces.

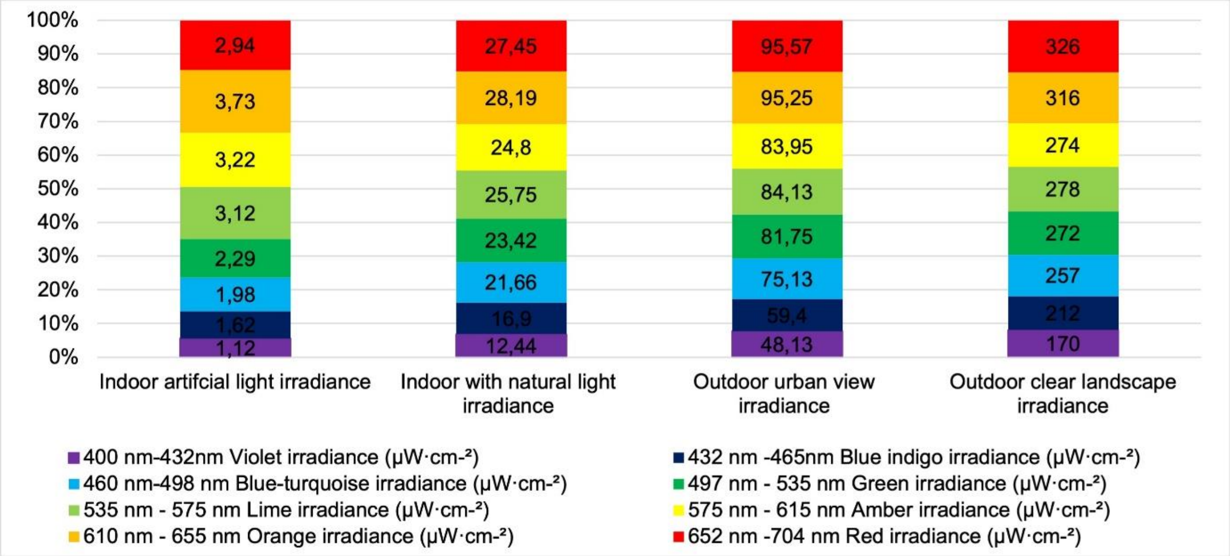

Figure 5 – Spectral signature of the four light environments with indoor artificial light, indoor situations with natural light (or a mixed light source because of possible additional artificial sources of light such as screens), open-space outdoor environments, and outdoor urban environments

Moreover, outdoor daily light dose accounted for up to 70% of the total light dose received daily. Blue light exposure was higher outdoors, particularly in open landscapes. The highest outdoors illuminance levels were observed in sunny conditions, while the lowest levels occurred on cloudy days. Although irradiance levels varied greatly according to the different weather situations in the same way as the illuminance, the light spectrum composition did not change. In all situations, light forms with longer wavelengths (in particular red and orange light) predominated over light forms with shorter wavelengths; the measured blue-violet light (400 nm - 452 nm) was the light form to which the participants were least exposed, accounting for 7% to 8% of the total spectrum.

3.3 Acceptability

The feedback from the participants was positive regarding the aesthetics and comfort of the Luca eyewears before and after the test. The main requests from the participants were to have more sizes available and the level of comfort of the bridge to be improved, notably through the addition of nose pads. The use of the Luca eyewears was described as easy and convenient by all the participants. The main constraints were cleaning the lenses, particularly as the participants were instructed not to pass the glasses under water. There were only a few reports of participants not wearing the Luca eyewears because they found them unpleasant or painful to wear, or due to glare. Similarly, there were only a limited number of reports of the Luca eyewears not being worn because of the occurrence of situations that were described as "risky" in the study protocol (i.e., sporting activities). One participant reported the loss of the cover of one proximity sensor. Other participants also reported that this cover was loose, but overall, the Luca eyewears were demonstrated to be sufficiently robust.

4 Discussion

This study demonstrated that this instrumented eyewear effectively measure light exposure in real-life conditions using an ALS, an 8-channel spectrometer, and proximity sensors. Reliable data were collected across various environments and weather conditions. Feedback was positive on aesthetics, comfort, and usability, with suggestions for more sizes and nose pads.

Despite minor issues, the instrumented eyewear proved robust and suitable for larger studies, highlighting their potential for continuous light exposure monitoring.

Time outdoors under high illuminance levels correlates with lower myopia rates (Ramamurthy et al., 2023), suggesting a protective role. Our study found participants spent a median of seven minutes per week above 10 000 lux, below the recommended 15 minutes daily (Bilu et al., 2020). This new instrumented eyewear uniquely measures light spectrum exposure, crucial for understanding light's effects.

However, our study had some limitations. The light sensors only approximate the light reaching the eye surface and do not consider face shape, so retinal light exposure cannot be accurately measured. Additionally, the sensors have a Lambertian profile, which does not reflect the real field of view of a human eye, and the device cannot determine where the participant is looking. Although the data allowed us to analyze near-cornea plane light exposure, our results cannot be generalized due to the small sample size and proof-of-concept design.

The findings support the optimisation of these new eyewear for future studies, which should include more participants, different seasons, and various locations to compare light exposures. Future improvements could involve adding clear and tinted corrected lenses for ametropic wearers, as well as a mobile app for easier data collection.

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