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A teaser made simple: a didactic measurement of the spectral answer of a human-eye-calibrated lux meter

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Abstract
A simple didactic experiment has been designed and realized, in order to illustrate to undergraduate students in scientific faculties some basic concepts lying behind the fundamentals of geometrical optics. The spectral response of a human-eye-calibrated lux meter was measured using a very trivial experimental arrangement. The white light of a halogen lamp was decomposed into its spectral components through a diffraction grating, so that collecting the radiation at different dispersion angles allowed one to measure the intensity as a function of wavelength. The experiment can be used to effectively illustrate the concepts of spectral distribution, the radiometry versus photometry conversion and photopic response, and the famous historical experience by Herschel on the 'temperature of colours'.

(Some figures may appear in colour only in the online journal)

1. Introduction

Spectral response and spectral sensitivity are the fundamental features of instruments for optical measurements and detection of light.

Despite the fact that the first photopic curve (the curve describing the spectral response of human eye in daylight vision) was proposed more than 80 years ago [1], and several adjustments have been consequently made [2–3], the question of the spectral sensitivity of the human eye is still attracting interest in the scientific community: the last correction was introduced after a very recent work [4], and studies on the eye response under several environmental conditions and healthy states are still being conducted [5–7]. Apart from the relevance from a physiological point of view, the question is very important concerning the differences in physics and in metrology between radiometric and photometric quantities, since the former are ‘physically’ built [8], while the latter are weighted through eye response [9].

The same kinds of measurements and considerations are necessary to characterize the instruments for detection of light. In particular, this is true if an optical instrument is required to have a specific spectral response, such as, e.g., human eye response. Such an instrument is called a *lux meter*. In a certain sense, a lux meter provides light measurement ‘simulating’ eye behaviour. Indeed, this instrument does not measure the ‘amount of radiation’ (in the sense specified in the next section) for each wavelength of the incident light; it has instead a different sensitivity for each wavelength, in the same way the human eye does. Therefore, the detection of light through a lux meter furnishes what a human subject would experience. In the next section, this point is developed in a quantitative way and through the appropriate physical quantities.

All these concepts are not always adequately inspected in physical courses at the academic level. The main reason is probably the specific fields of application, more limited than many other topics. However, as stated above, the relevance of these arguments lies beyond their specific applications; they are capable of illustrating important aspects of metrology and making a student face problems typical of measurements in optics. Considering the importance of such questions from an empirical point of view, an adequate place in experimental physics and laboratory courses should be reserved for them.

In a recent paper [10], the importance of assembling laboratory spectrographs for undergraduate students was stated. In this paper, on the other hand, we propose and describe a simple didactic experiment, inexpensive in cost and effort, complementary to the spectral characterization of light by a spectrograph: the measurement of the spectral response of a light detector from a known light source, with particular mention of lux meters as instruments ‘simulating’ the human eye working. The experiment has been assigned during practice hours for students of optics; in the following, we describe the apparatus, the results and the faced problems, and the impact on the learning process.

2. Radiometry and photometry: the goal of the described experience

Basically, the relationship between the fields of radiometry and photometry is established by the following formula:

$$\Phi = 683 \cdot \int_{\mathrm{Spectrum}} V(\lambda) P_\lambda(\lambda)\, \mathrm{d}\lambda. \tag{1}$$

Here, Φ is the luminous flux, in lumen, from a source having the spectral emission power $P_\lambda(\lambda)$. The function $P_\lambda(\lambda)$ (measured in W m^{-1} in SI units, or, more commonly, in W nm^{-1}) describes how the emitted power (in W) is distributed over the electromagnetic spectrum, i.e. as a function of the wavelength λ. Having P as the whole power emitted by the source, the spectral power is defined by

$$P = \int_{\mathrm{Spectrum}} P_\lambda(\lambda)\, \mathrm{d}\lambda. \tag{2}$$

$V(\lambda)$ represents the luminous efficiency function for the human eye in daylight vision, the so-called photopic visual response function, which gives the relative sensitivity of the human eye to the different light wavelength. In (1), $V(\lambda)$ is intended to be normalized so that its peak value is 1. Comparing (1) and (2), and ignoring the factor 683, it can be argued that this is how the ‘physical’ power is not entirely transmitted to the receiving subject, since the function $V(\lambda) \leqslant 1$ in the former is replaced in the integral by a ‘factor’ 1 in the latter. The multiplication by 683 is to define the photometric unit lumen: 1 lm corresponds to the power of 683 W at $\lambda = 555$ nm (which is the wavelength value where $V(\lambda)$ has its maximum value, i.e. 1).

Each optical detector, other than the human eye, has its own 'luminosity function' and in principle each one could define a set of units; however, due to its particular relevance, the luminosity function of the human eye has been used to define the specific set of the photometric units (units other than the radiometric have been introduced only for some very technical and specific fields such as photography).

All these concepts, including the unit conversion given and considering a well-defined wavelength, can be, in our opinion, more easily understood if a student can empirically experience the conversion from radiometric emission and photometric perception.

Among the light detectors, the lux meter has the peculiar feature of directly providing an answer in photometric units; this is the ultimate meaning of an instrument having the same spectral response as that of our eye. It measures the illuminance, i.e. the luminous flux incident on a surface per unit area, which is measured in lux (lx) in the SI unit; the illuminance is therefore referred to the receiving surface and not to the source (actually the same unit, with the same definition and meaning, is used for the luminous emittance when referring to the source). The lx is analogous to the radiometric unit Watts per square metre (W m^{-2}); simply, the power carried by each wavelength is scaled by the photopic response function $V(\lambda)$.

According to these considerations, the characterization of the response of a common commercial lux meter to the light emitted by a known source can be very powerful for illustrating in a simple and reliable way the relevant concepts.

3. Description of the experiment

In the experiment, we recall the famous work by Sir Frederick William Herschel in 1800 [11–12]. He tried to measure what he called the temperatures of the colours of sunlight. The light was known to be decomposed by a prism in its colours. Herschel argued that each colour was carrying a different 'amount of heat', and he decided to set up an experiment to measure the heat, or the temperature, associated with each colour.

The idea was very simple. Collecting the light colours, separated by a glass prism, on a 'cold' surface, he measured the temperature variation due to each colour (by comparing the temperature of each part of the coloured surface with a portion far away from the illuminated region). Of course, reviewed with modern knowledge, that experiment suffered from many incorrect assumptions, and it is still known and cited because it allowed one to discover the existence of infrared (by placing a thermometer just aside the red part of the projected light). The main unaccounted feature, under the point of view of photometric questions, was that he did not consider the power distribution of the sunlight over the different colours. In other words, the measured temperatures, even in the case where they could represent a quantitative property of the investigated phenomenon, were not an absolute feature of the colours themselves, but instead they reflected a property of the source of light. In addition, a possible spectral thermal response of the bulb of the thermometer to the different colours was not considered (blackened bulbs were used for better absorption of light; however, of course, no quantitative estimations were possible about the absorbed energy fraction for each colour).

We transpose the simple idea to a reverse purpose: not to measure the feature of the incident radiation, but to characterize the spectral response of the light detector. As stated in the previous section, the choice of a lux meter was made because the instrument is supposed to reproduce the human eye spectral response. This gives the teacher an opportunity to introduce the ideas of photometric versus radiometric units and quantities, and to experimentally show the concept of spectral response curve. In this experiment, we used a commercial lux meter

(ISO-TECH ILM 350 RS). The recorded response curve will be compared with that provided by the manufacturer to accomplish the didactic purpose of the performed experiment.

In order to obtain a satisfactory wavelength resolution, much better than the 'seven rainbow colours' studied by Herschel, we used a diffraction grating (an accessory always present in an academic laboratory of optics) to decompose white light into its spectral components.

Keeping the analogy with the experiment by Sir F W Herschel, the diffraction grating realizes the separation of the different spectral components of the light (the colours in Herschel's experiment) as a function of the angle of detection (the analogous of the position on the table). The lux meter (instead of the bulb thermometers) is placed to collect the incident light after its decomposition, in order to measure its weighted spectral power per surface unit (which replaces the heat or the temperature in the original idea by Herschel).

The adopted source is a Philips Focusline halogen lamp, type 7724, EVA M 28. The lamp has a GY6.35 fitting and is supplied with 12 V; its other features include an emission power of 100 W, an emission temperature of 3100 K and luminous flux of 3600 lm (efficiency is 36 lm W^{-1}).

Everything was mounted on a commercial optical bench produced by LD Didactic GmbH. It is easy and cheap to obtain, along with the lux meter, the halogen lamp and the diffraction grating, being the basic equipment of any didactic laboratory of optics. In this way, the assembly of the apparatus and the preparation of the experience follow the movement towards cost efficiency, a remarkable featured in optics laboratories for a long time [13].

The goniometer sensitivity is 0.5°; converted in λ, it means a sensitivity on the first and second orders of about 13 and 5 nm, respectively. The experimental points were collected by displacing the goniometer with steps of 1°. The distance between the grating and the slit before the lux meter was kept at 5 cm; with angular steps of 1°, it gives a corresponding lateral separation of about 0.9 mm. The slit width is 0.4 mm, well below such separation: this guarantees that for each experimental point, the collected amount of light is not affected by a contribution coming from neighbouring points.

In figure 1, a sketch representing a parallel between the Herschel experiment and the experience we are proposing is given, together with a picture of the experimental apparatus we set.

4. Results and discussion

The angular position θ of the collected light with respect to the diffraction grating can be converted into light wavelength λ through the well-known Bragg formula for the position of the diffraction maxima:

$$m\lambda = d\sin(\theta) \Rightarrow \lambda = \frac{\sin(\theta)}{mt}. \tag{3}$$

In the above formula, m (=1, 2, 3, ...) defines the order of the maximum and d is the slit separation on the grating; $t = d^{-1}$ is the number of slits per unit length. In our grating, $t = 600$ lines/mm (6×10^{-4} nm^{-1}). Through (3), at a fixed order, any angular position θ of the detected diffracted light can be converted in the corresponding wavelength value λ. The possibility of measuring more than one order of maxima provides a check of the validity of the approach.

The zero-order light obviously converges in the zero angular position for any wavelength. This fact is used to identify the position $\theta = 0$. Figure 2 shows the shape of the central (zero-order) maximum. The origin of the angles is taken at the maximum measured value. In addition, from a didactic point of view, recording the zero-order light distribution gives the

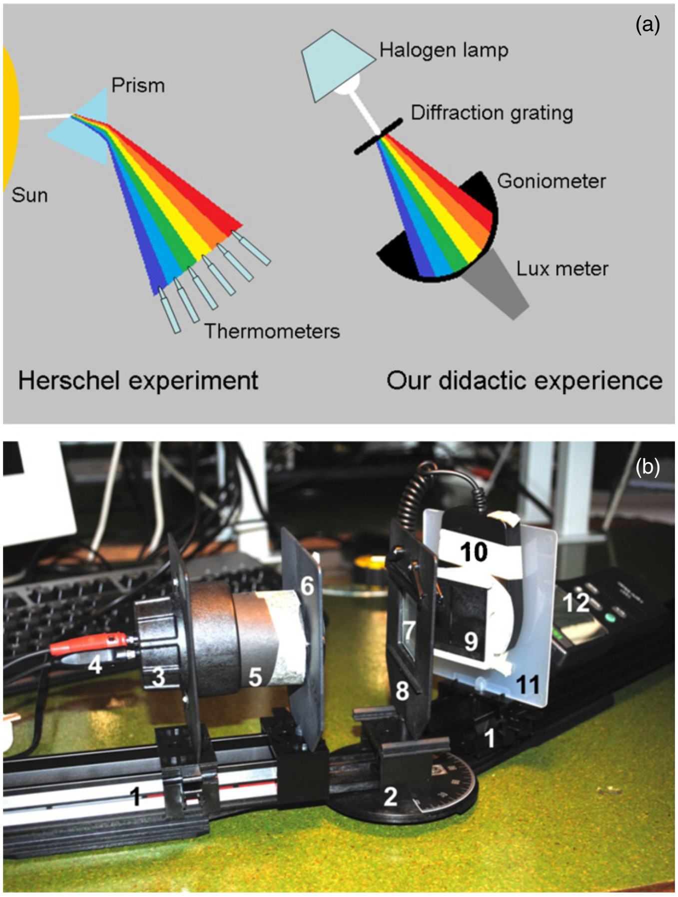

Figure 1. (a) Comparison between the ideas of the Herschel experiment and the didactic experience illustrated in this paper. (b) A photograph of the experimental apparatus: (1) optical bench, (2) optical bench goniometer, (3) white light 2300 K source, (4) light power supply, (5) external light shadowing tube, (6) 1 mm diameter diaphragm, (7) 600 mm^{-1} lines diffraction grating, (8) diffraction grating holder, (9) 0.4 mm slit, (10) lux meter active device, (11) lux meter active device holder and (12) lux meter measuring display; the gap between (8) and (9) ranges from 2 up to 5 cm.

opportunity to verify the theoretical prediction about its width (or, alternatively, an estimation of the slit separation), through the equation of the angular position of the first dark fringes:

$$\frac{\lambda}{2} = d\sin(\theta_{\mathrm{FirstMin}}) \Rightarrow \theta_{\mathrm{FirstMin}} = \arcsin\left(\frac{\lambda}{2d}\right) = \arcsin\left(\frac{\lambda t}{2}\right). \tag{4}$$

In our case, the additional exercise is in the estimation of the λ value to introduce in (4). The ultimate width is given, in principle, by the dark fringe position of the highest detectable wavelength. Using $\lambda \approx 700$ nm, with $t = 6 \times 10^{-4}$ nm^{-1}, we obtain $\theta_{\mathrm{FirstMin}} \approx 12^{\circ}$. For the determination of the position $\theta = 0$, it is important that the error in the detection of the maximum value is of the zero order; as shown in figure 2, it is below the goniometer sensitivity.

In figure 3, the measured curve for the first order is overlapped with the curve provided by the manufacturer. The vertical error bars on the illuminance values are calculated as a statistical error over repeated measurements, while the error in the wavelength is given by the error when reading the angular position. Within the experimental error, the simple adopted

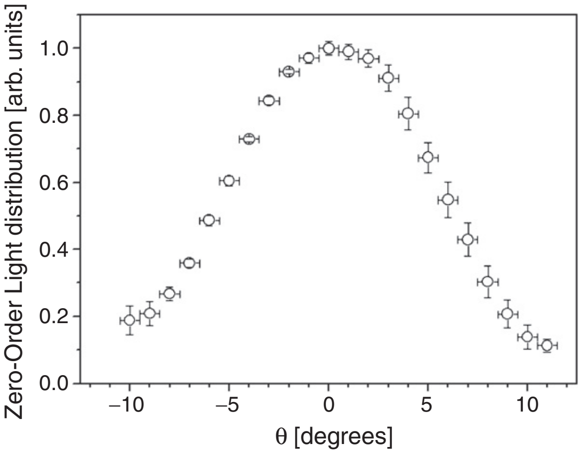

Figure 2. Light distribution for the central maximum to determine the zero of the angular position.

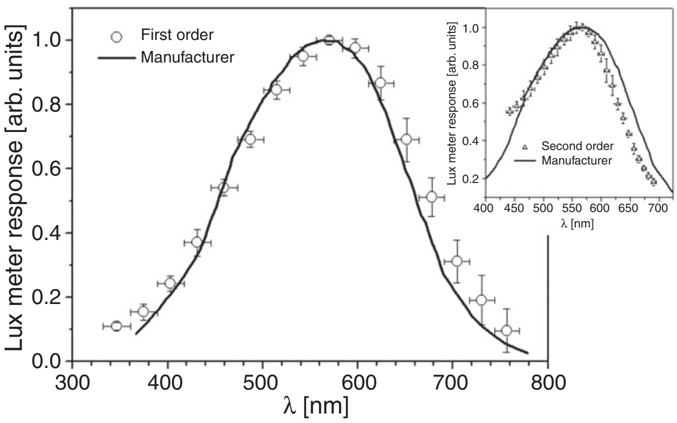

Figure 3. The experimental curves for the lux meter response, evaluated as described in the text from the spectral distribution of the first- and the second-order diffraction maxima. The illuminance for the first and (in the inset) the second order is overlapped with the lux meter response curve provided by the manufacturer.

procedure well reproduces such a curve through the measured data. The inset reports a similar procedure for the second order. In this case, the measurement and the comparison with the manufacturer curve are more difficult because of geometrical problems and, moreover, for the larger angular spread and smaller intensity of the illumination. Its importance, therefore, is purely didactic, and the comparison between the peak positions of the curves represents a further confirmation of the reliability and quality of the experiment.

It must be pointed out that the first two orders' contributions do not substantially affect each other. Indeed, the maxima of the first- and second-order curves at wavelength of about 560 nm are located at angular positions close to 20° and 43°, respectively; 27° nearly corresponds to wavelengths of 750 nm for the first order and 380 nm for the second order, which are the wavelengths at the edge of the sensitivity range of the eye and of the lux meter (the sensitivity is reduced by almost an order of magnitude compared to the peak values, making negligible the overlapping of the tails). The same can be said about the separation between the dispersion curve produced by the first order and the central maximum (380 nm corresponds, in the first order, to 13°).

The curves reported in figure 3 represent the final output of the measurements, i.e. the result of the didactic experience: a sort of measure of how the eye weigh the white light as a function of the wavelength.

It is important to put forward evidence that a hypothesis underlies the experiment: a flat emission spectrum from the source would ensure that any measured difference of incident intensity as a function of wavelength will depend on the detector. The manufacturer did not provide the detailed emission spectrum. However, it is apparently far from a pure black body radiation at the corresponding colour temperature, since such a spectrum would have required a major correction of the output curve (the detected intensity at each wavelength being affected by very different values of emitted intensity from the source). In contrast, we observed the curves reported above, which are in good qualitative agreement with the expected response curve of the lux meter. It is likely that the emission spectrum is affected by several occurrences, such as the emission spectrum of solid tungsten and the presence of filters, which often make the halogen lamps spectra not flat but with reduced differences in the visible region (to get an eye-comfortable white perception). The quantitative discrepancies (especially for the second-order curve) between the measured curve and the expected one are, however, to be ascribed mainly to the approximation of flat emission spectrum. The students were made aware that a correction from such an effect should have been made. However, besides the absence of the emission curve, a fine correction was beyond the didactic purposes of the experiment.

From this point of view, it is interesting to report that a first realization of the experience gave us encouraging results. At present, it has been proposed as a traineeship class in optics. The trained students were found, by the commission, to understand the underlying concepts better than the average classes so far examined. In particular, the experience furnished solid basis to face different problems involving the same concepts. We interpreted this as a sign of a real understanding of the conceptual basis rather than a mere learning of the features of a specific problem. It can be ascribed to the effectiveness of 'teaching through problems' in supporting critical ability and improvements to the students' attitudes towards scientific disciplines.

5. Conclusions

Despite the conceptual simplicity, the described procedure provides a simple and reliable method to measure the spectral response curve of a light detector. The experience is didactically, effective since it involves the application of optics, spectral measurements, curve deconvolution and the question of the luminosity function as representative of an optical instrument. The characterization of an instrument, i.e. the lux meter, which is supposed to reproduce the behaviour of the human eye, adds the opportunity to introduce photometric units, defined in conjunction with the radiometric (physical) ones to take into account the spectral sensitivity of the human eye, which weighs the spectral response in many fields. All the measurements have been performed using simple equipment, and the resulting spectrometer can be reproduced easily in any academic laboratory of optics.

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