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Studying colours with a smartphone

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Summary. — We show how a low-cost spectrometer, based on the use of inexpensive diffraction transmission gratings coupled with a smartphone photo camera, can be assembled and employed to obtain quantitative measurements of spectra from different sources. The analysis of spectra emitted by different light sources (incandescent bulb, fluorescent lamp, gas lamps, LEDs) helps students understand the different physical mechanisms which govern the production of light. Measurements of emission and transmission spectra allow students to focus on the differences between additive and subtractive models of colour formation. For this purpose the spectra of RGB colours emitted from an LCD screen and the transmission spectra of CMY pigments of a laser printer have been studied, using our low-cost spectroscope. A sequence of experimental activities was designed, and proposed to undergraduate students and secondary school teachers in order to study the feasibility and educational potential.

1. – Introduction

In recent years several inexpensive educational apparatuses, based on the employment of digital photocameras *e.g.* smartphone cameras, have been used for spectral measurements [1-3]. We designed standardized variants of low-cost spectrometers, where the differences in design depend on the type of grating used. Such spectrometers can be assembled very quickly (about one hour) using inexpensive materials and allow carrying out wavelength and light intensity measurements with good accuracy. By means of these apparatuses students can apply spectroscopic techniques both to the study of different light sources (different light bulbs, spectral lamps, LCD monitors), and to the diffusion/transmission mechanism of colour filters or pigments. Their work can be finalized to address the following problem "*what is the origin of the perceived colours?*" in a quantitative manner especially by analysing the spectrum of different colours produced by a monitor or diffused by the pigments printed by a digital laser printer. In particular using a smartphone as detector and a PC monitor as source, students investigate the main features of additive colour synthesis, and how colours are produced on digital displays [4], then using the coloured ink lines, printed by a laser printer, they can explore the physical grounds of the subtractive colour model. The sequence of activities is aimed

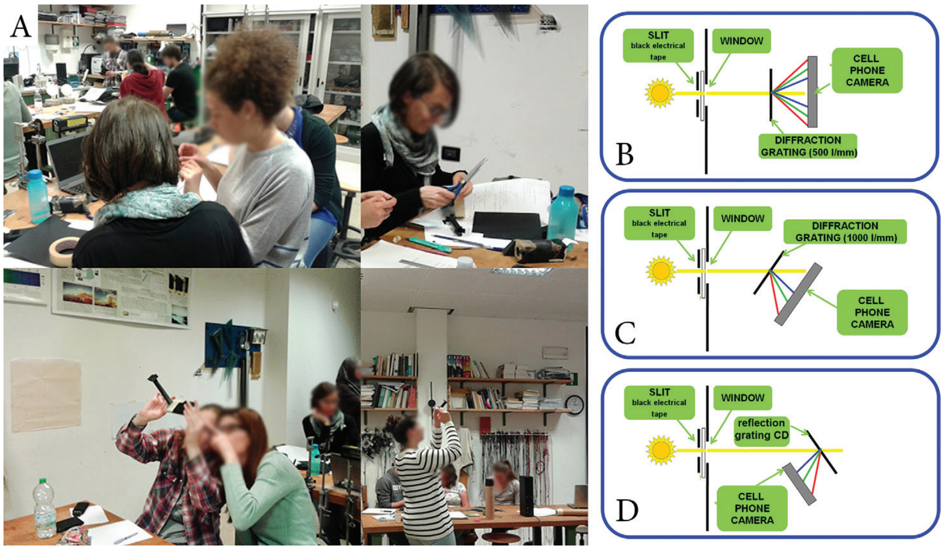

Fig. 1. – (A) Students sassemble and use their own spectroscope using a black cardboard frame: a parallelepiped cardboard tube with a hole for the cellphone camera on one side and a narrow slit made by a cutter on the other side. The experiment's scheme: the light entering the slit is transmitted with an angle strongly dependent on the wavelength. (B-D) The three different versions of the apparatus, the first one (B), $S_{500,}$, employs a 500 l/mm transmission grating with direct geometry, the second one (C), S_{1000} utilizes a 1000 l/mm transmission grating with light entering with a different incident angle, the third one (D) uses a reflection grating (colour on-line).

at both high school and undergraduate students and has been proposed, in the last two years, for preliminary testing both to undergraduate students and to pre service and on service high school teachers at Universities of Trento and Pavia. In sect. **2** we show how a low-cost spectrometer, based on the use of inexpensive diffraction transmission gratings coupled with the cellphone's photo camera, can be assembled and employed to obtain quantitative spectra. In sect. **3** we discuss how students can use the spectroscopic technique to study the radiation emitted by different sources or transmitted through paper sheets with colours stamped by laser printer. In sect. **3**˙1 we mainly focus on the characterization of different sources, while in sect. **3**˙2 we use the measured spectra of light emitted by a LED PC monitor and the one transmitted by coloured ink lines produced by a laser printer to explore the physical grounds of colour theory.

2. – The spectrometer

2˙1. *How to make your hand made spectrometer*. – In fig. 1([1]) we show three different versions of the apparatus based on a smartphone camera. We assembled two kinds of spectrometers using a transmission diffraction grating. The first one, S_{500} (fig. 1(B)), employs a 500 l/mm transmission grating with a direct alignment, the second one, S_{1000}

([1]) Figures from 1 to 7 are printed in black and white but they are visible in colour in the on-line version retrievable through the DOI of this paper.

(fig. 1(C)), utilizes a 1000 l/mm transmission grating with a non-linear geometry. A third spectrometer (fig. 1(D)), was employed in the past [2, 5] and uses a reflection diffraction grating, made with a Compact Disk (500 l/mm) with a non-linear geometry configuration. All the spectrometers are assembled by means of a black cardboard frame. A narrow window is opened at the distal end of a collimating tube. For the transmission measurements the window is covered by a white paper sheet (where ink lines can be drawn). The slit produces a narrow enough beam of light. The transmission gratings, on the opposite side of the tube, disperse the beam of light into spectral lines with different colours at different angles. The tube, in combination with the slit, acts to ensure that only approximately collimated light is focused by the camera lens on the smartphone.

Since the 1000 lines grating and CD reflection gratings require that incoming light from the source is not perpendicular to the grating, they can be slightly less straightforward to build for inexpert students. Thus, students in our tests assembled their own spectrometer, S_{500}, by employing a 500 lines mm^{-1} transmission grating. Student captured photos with their own smartphone using the free app OpenCamera which allows to manually set the camera's focus (in order to have it constant among different measurements), ISO and exposition. The images acquired by means of the camera are analyzed with the Tracker video analysis software which provides direct measurements of RGB channels and of the brightness pixel by pixel along a line profile.

2$\cdot$2. *Calibration procedure*. – The calibration procedure for the spectrophotometers requires two steps: the wavelength calibration (λ-calibration) and the intensity calibration (I-calibration).

λ **calibration**. A commercial fluorescent lamp is used to calibrate the spectrometer (the full procedure is described in [6]). The spectrum of this lamp shows many peaks distributed over the range of wavelengths of visible light. Once acquired the pictures of the spectral lines, students accurately measure the positions of their peaks by using the free video analysis software Tracker [7]. Comparing the experimental findings with the known wavelengths of the fluorescent lamp's peaks they can obtain the calibration curves which represent the peak positions (measured in pixel) *versus* the known wavelength. These curves are adequately fitted by straight lines. The uncertainty in the wavelength measurement inferred using these fits is below ± 2 nm for the S_{1000} and ± 3 nm for the S_{500}.

What are we measuring? Tracker can measure the brightness, in luma, along a line in an image using a "line profile" tool. To get the measurement of light intensity from RGB values for a jpeg image generated by a cellphone, we use the formula

$$Y_{\text{measured}} = 0.2126\ R^{\gamma} + 0.7152\ G^{\gamma} + 0.0722\ B^{\gamma}(2),$$

where Y is a measure of luminance, which is proportional to emitted light intensity per unit area, and $\gamma = 2.2$ is the factor expressing how the luminance on the screen in the image depends on the 8-bits RGB colour values (ITU-R Recommendation, 2002) [8].

The validity of the above formula is controversial and some authors suggested to use Raw images [9], but, unfortunately, cellphones not often produce this kind of images. However the validity of γ-correction was recently discussed and tested with experiments, which have shown the effectiveness of this approach [10].

I-**calibration**. The value of luminance obtained also depends on the overall response of the apparatus (CCD camera, lenses and so on). As such, we have to evaluate the

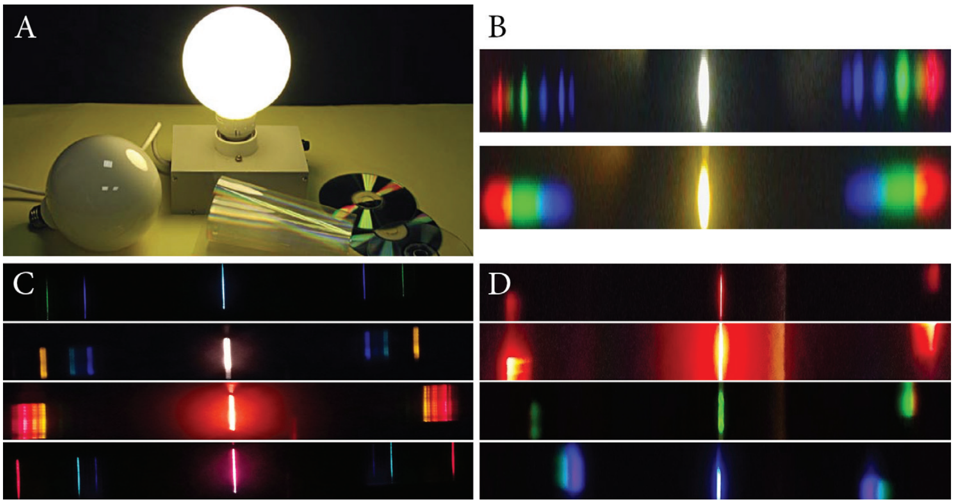

Fig. 2. – (A) Two undistinguishable lamps, a fluorescent and a filament bulb. (B) Comparison between the spectra of a commercial fluorescent lamp and an "old" filament light bulb, showing the differences between a continuous and a discrete spectrum. (C) Atomic spectra obtained by students using their home made spectrometers. (D) Spectrum of 4 LEDS, from top to bottom Red, Orange, Green and Blue (colour on-line).

relative sensitivity (or "spectral response", see ref. [11]) of the apparatus by measuring the light spectrum from a known source. We use known data for the spectral irradiance, $I_{S0}(\lambda)$ of a solar disk on Earth's surface and compare that with our measurements of the solar spectrum, $Y_{S0}(\lambda)$. Thus we experimentally obtain the relative sensitivity, $R(\lambda) = Y_{S0}(\lambda)/I_{S0}(\lambda)$, (reported in ref. [2]) which converts the measured luminance in the actual intensity, in arbitrary units, for any source ($I(\lambda) = Y(\lambda)/R(\lambda)$).

3. – Emission versus transmission spectra

3˙1. *Light sources* . – Using the homemade spectrometers students were able to investigate the different light sources and better understand the physical mechanisms which govern the light emission. Students, after the construction of their own spectrophotometers, performed direct spectral measurements of different sources of light (In fig. 2(A)) the light emitted by a fluorescent lamp and by an incandescence bulb are compared to show the differences between a continuous and a discrete spectrum). Students also measured the quasi-monochromatic light emitted by LEDs and analyzed the broadening of the peaks, visible in the photo as a red band in the emission of a green LED or a cyan band in the emission of a blue LED. Students could compare the spectra of a compact fluorescent lamp and of an incandescent bulb, thus they investigated the spectra of many different spectral lamps (H, He, Ne, Ar, Hg) looking for the fingerprints of the emitting substance (see fig. 2).

Students were also required to measure the wavelength of visible lines of Balmer series from the hydrogen atom spectrum and estimate the value of Rydberg's constant. The values of the Rydberg constant measured by students was $R = 1.097 \pm 0.004 \times 10^7\ \mathrm{m}^{-1}$ with an error difference less than 0.06%compared to the accepted value of $1.097\ 373 \times 10^7\ \mathrm{m}^{-1}$.

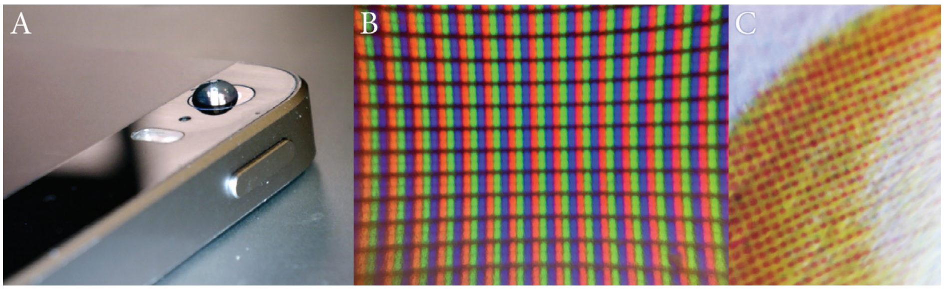

Fig. 3. – (A) The cheap macro lens: a small droplet of water can be used to take photos of the monitor's pixels. (B) Photos of the monitor colours: the RGB triads are well visible. We use the monitor of a MacBook Pro (Retina, 15-inch, Mid 2015). (C) Orange strip of colour painted by a laser printer observed through the low-cost microscope (colour on-line).

3˙2. *An insight in colour theory* . – Measurements of emission and transmission spectra may allow students to focus on the differences between additive and subtractive models of colour formation. Students performed direct spectral measurements of colours produced by a laptop's monitor and a common printer.

The colour produced by a LED monitor is a good example of the RGB (Red, Green and Blue) additive colour model while the colour lines produced by a laser printer using the CMYK (Cyan, Magenta, Yellow and Black) method can help students to understand the subtractive colour model. Thus the spectra of RGB colours emitted from an LCD screen and the transmission spectra of CMY pigments of a laser printer have been studied by students, using their handmade low-cost spectroscopes.

A microscopic analysis of the samples producing the colours helps students to understand spectroscopic results. Thus students inspected the colours displayed on a monitor or printed on paper on a "microscopic" scale employing a rudimental microscope obtained using the smartphone camera and a water droplet. In fact placing a drop of water on the lens of a digital camera essentially turns it into a macro lens.

Any colour shown on a monitor results from a mixture of the three RGB LEDs corresponding to a Pixel on the screen, and any colour printed on a paper sheet results from a mixture of the three CMY pigments.

3˙3. *Spectra of colours emitted by computer monitors and additive mixing of colours*. – Displays of modern devices use the RGB additive colour mixing to create images. Each pixel is characterized by a triad of physically separated elements as shown in fig. 3. A typical 8-bit monitor features $2^8 = 256$ different intensity levels for each RGB triad element, resulting in about 16.7 million different colours. Students used the spectrophotometer to analyse the spectra of different colours displayed on a MacBook Pro (retina display, 15-inch, mid 2015). In fig. 4 a collage of the spectra and the corresponding plots showing intensity *versus* wavelength (obtained with Tracker) are shown.

Any colour shown on a monitor results from a combination of the three RGB peaks, *e.g.* the white spectrum results from the sum of all the three components, as well as the cyan, magenta and yellow spectra result from the sum of two of the three components. A quantitative comparison between students' measurements and theoretically expected values in terms of the CIE *xyz* colour space may be done as described in [4].

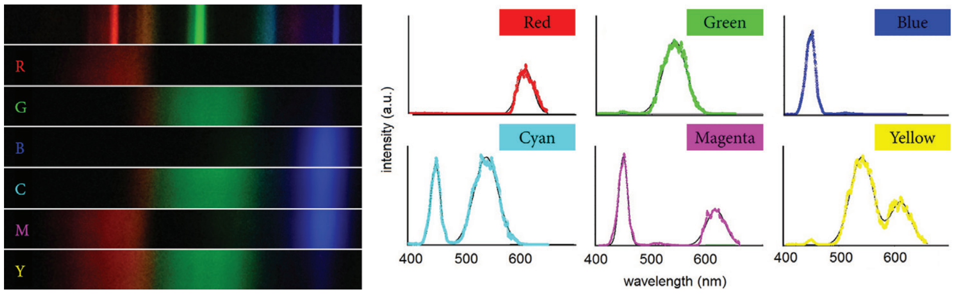

Fig. 4. – The intensity of photoemission, $I_P(\lambda)$ measured by the spectrometer for the different colours on the monitor. Left: Collage of the acquired photos used for the measurements. On the top the spectrum of the fluorescent lamp used for the wavelength calibration (λ-calibration) is shown. Strips *R, G, B, C, M, Y* come from photos of the spectra when the screen produce definite colour. Right: $I_P(\lambda)$ is reported in arbitrary unit on the same scale of intensity for all the panels (colour on-line).

3˙3.1. Printers and subtractive mixing of colours. Printers produce all the colours by mixing cyan, magenta and yellow pigments on paper: this is the basics of CMY subtractive colour mixing (fig. 5). Since pure black cannot be obtained using non-ideal pigments, a black pigment is also used. Laser printers leave coloured dots of different sizes accordingly to the desired intensity of the CMY pigments. As a result, some areas will be covered with pure CMY pigments, some with a mixing of pigments, and others will be left without any. However, as in the previous case of display pixels, a uniform colour is perceived by the human eye by additive colour synthesis of these different areas.

The transmission spectra of different printed colours were analysed by putting printed coloured strips on top of the spectrometer and using sunlight as a (white) light source.

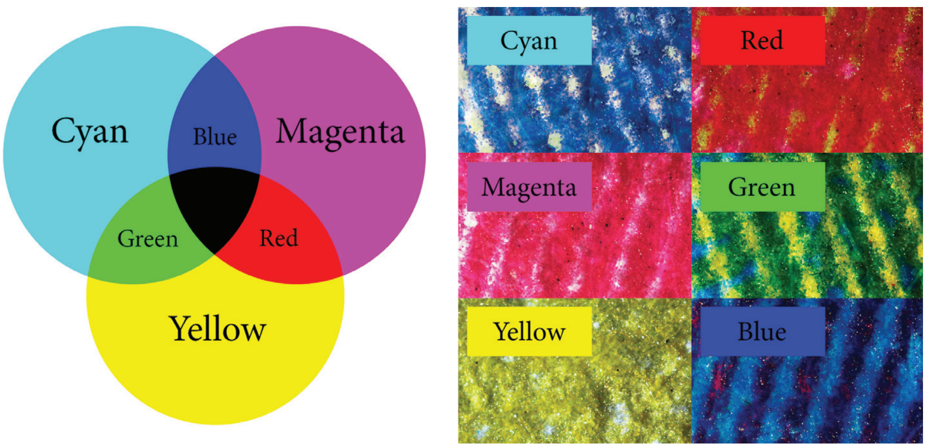

Fig. 5. – Left: The CMY subtractive colour model. Right: Macro photos of printed colours (on the left, the pure, fully saturated CMY pigments; on the right, the RGB colours obtained as the addition-subtraction of two CMY pigments). Typical widths of the strips are about 0.15 mm. The laser printer used is a Samsung CLX- 3305FN (colour on-line).

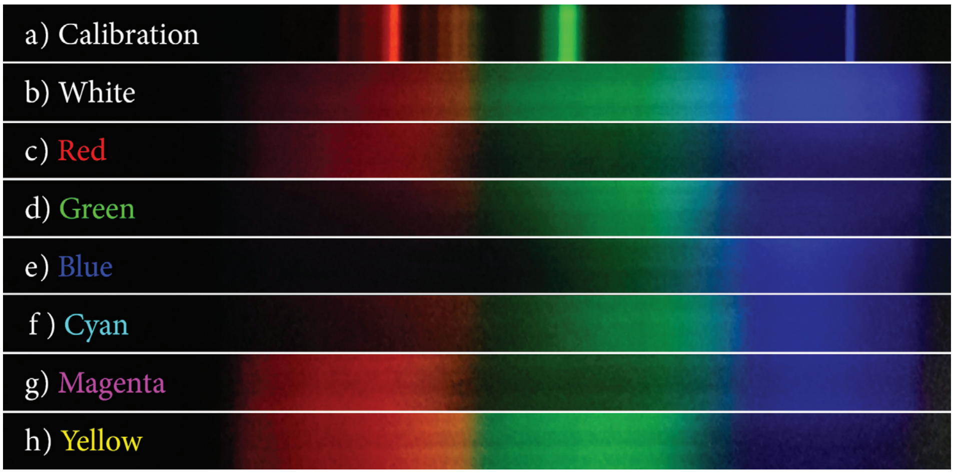

Fig. 6. – Strip (a) shows the spectrum of the fluorescent lamp used for the wavelength calibration (λ-calibration). Strips (b), (c), (d), (e), (f), (g), (h) come from a single photo of the spectra of sunlight passing through the coloured ink lines (c)–(h) and white paper (b). Strip (b) is also used for the Intensity calibration (I-calibration) (colour on-line).

A collage of the spectra collected by students is shown in fig. 6.

In order to measure transmittance we need to compare the spectra of the sunlight passing through the white paper sheet and the spectra of the light transmitted by the coloured paper sheet recorded under identical conditions. We use a single photo where both the transmitted and the original spectra are acquired.

By comparing the intensity measured when sunlight traverses the white sheet only, and the one measured when it passes through the coloured lines, we can measure the transmittance as a function of the wavelength λ. Transmittance, $T(\lambda)$ of a sample of a material is defined as its effectiveness in transmitting radiant energy. It is the fraction,

$$T(\lambda) = \frac{I_T(\lambda)}{I_0(\lambda)},$$

of incident electromagnetic power, $I_0(\lambda)$, that is transmitted through the sample. We identify $I_0(\lambda)$ with the measured intensity through the white paper, $I_T(\lambda)$ with the measured intensity. As can be seen in fig. 7, cyan acts as a low-pass filter (referring to wavelengths), magenta as a band-stop filter, and yellow as a high-pass filter.

Comparing these results to the ones corresponding to printed red, green and blue colours (bottom panels) it can be intuitively seen as the subtractive colour mixing can more accurately be referred to as a multiplicative one. In fact, the red spectrum may be approximated as the product of magenta and yellow spectra, green as the product of cyan and yellow, and blue as the product of cyan and magenta. It can be highlighted how green acts as a pass-band filter, resulting from the action of both a low-pass (cyan) and a high-pass (yellow) filter.

4. – Using the apparatus with students and teachers

The activities have been proposed, in different sessions, to both undergraduate students, pre service teachers and on service secondary school teachers, in order to study

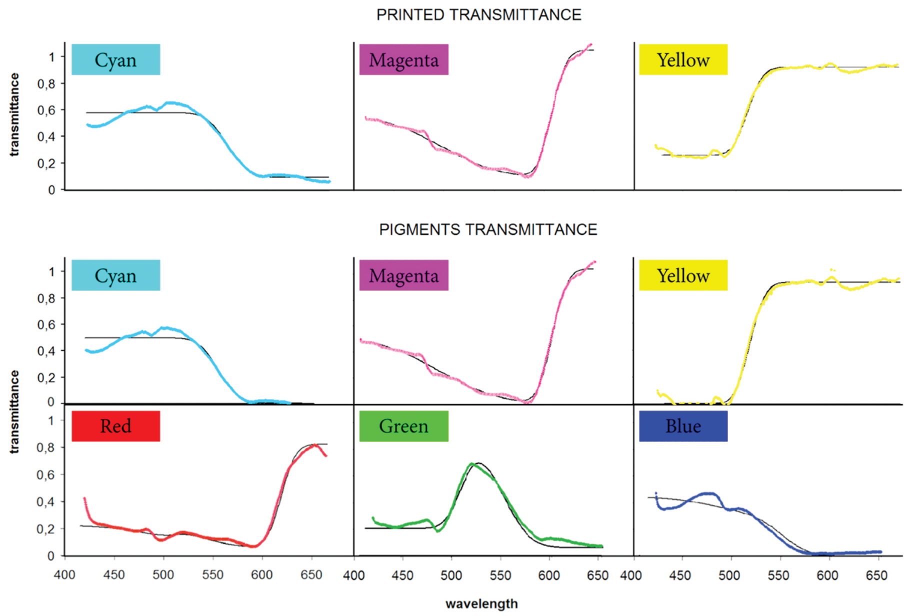

Fig. 7. – Transmittance $T(\lambda)$ as measured by the spectrometer for the different primary CMY colour printed lines (top). Extrapolated transmittance of the corresponding pigments obtained by subtracting the contribution of white unprinted regions (bottom). The $T(\lambda)$ for the primary colours are fitted using an erf function model. To reduce the noisy appearance of the transmittance curves a moving average smoothing with a 10 nm width was introduced. Transmittance $T(\lambda)$ measured by the spectrometer for the different RGB colour printed lines. The transmission spectra of pigments were fitted using the erf function to describe transitions from high to low transmittance (colour on-line).

their feasibility and educational potential. A positive influence of the activity in the process of appropriation of experimental methods emerges clearly from the results of our study. We report some of the final comments, in which teachers and students highlight the formative role played by these activities. Most comments refer to

- The relation between light and colours : "*These activities are not aimed to clarify doubts derived from the theory, but rather to invite students to reflect on the nature of light and colour and to question what they thought they knew. For example, often when we see two light bulbs, these seem the same, but deepening the study with the use of spectroscopes we realize the differences that the naked eye does not notice.... we are surrounded by the colours but we do not ask what they really are and how they are formed.*

- The smartphone-based spectroscopy, the image analysis and the tools: *"The use of image analysis can be a useful tool to introduce and bring to physics all students.... thanks to this experimental approach, while not knowing all the theory that explains these phenomena, the students are able to see and understand, from a more quantitative point of view, both wave phenomena of light and colours, since they can measure the spectrum of a light source."*

- The value of the experimental activities in constructing the scientific knowledge: *"The activity is useful because it allows you to experience first hand the difficulties* *involved in the process of experimental measurement... it provides a good idea of the work of the scientists... it allows you to work effectively on the specific skills of scientific inquiry"*. Or: *"You explore what the typical steps of an experimental investigation are: identification of a goal, ... the need to calibrate an apparatus, ..., the need to analyze the data collected by assigning the values of the measurements as well as their uncertainties...."*

5. – Conclusions

In this paper we discussed how a low-cost handmade spectrometer, based on the use of diffraction gratings coupled with the smartphone photo camera, can be assembled and employed to obtain quantitative spectra of different sources. The activities allowed students to understand that different physical mechanisms are responsible for the production of light.

Measurements of emission and transmission spectra may allow students to focus on the differences between additive and subtractive models of colour formation. For this purpose the spectra of RGB colours emitted from an LCD screen and the transmission spectra of CMY pigments of a laser printer have been studied using our low-cost spectroscope, and a sequence of experimental activities was designed.

This experimental approach to colours was designed for undergraduate and highschool courses or interdisciplinary courses/workshops on science and art. The sequence of experiments was tested with undergraduate students, pre service teachers and in service secondary school teachers.

When tested with undergraduates the activities showed effectiveness in raising students' interest in the subject, and improving their understanding. Teachers, both in service and in training highlighted the formative role played by these activities. A positive influence of the activities in the process of appropriation of experimental methods emerges clearly from the outcomes of our tests.

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