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Introduction to Light Properties and Basic Principles of Spectroscopy at the High-School Level: A Pilot Study

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Abstract: Spectroscopy is the basis of many applications in chemistry; however, the basic principles of light, light–matter interaction, and the operation of spectrophotometers are rarely present in chemistry curricula at the high-school level, or they are only briefly introduced to students before focusing on analytical chemistry applications. In this work, we report the results of a study conducted over several years, aimed to design, optimise, and put into practice a didactic sequence on light phenomena such as reflection, refraction, interference, diffraction, and light dispersion, as well as the basic principles of ultraviolet–visible spectroscopy and spectroscopic instruments. Difficult concepts of light phenomena and related topics were deeply investigated, focusing on the best ways to teach them to high-school students in the framework of the content-specific components identified in the topic-specific pedagogical content knowledge theoretical model. Inquiry-based learning and interactive STEM laboratory activities were combined with a historical epistemological teaching method. Short introductory videos were also recorded to help students during the remote lessons in the COVID-19 pandemic period. In this paper, we report and discuss the research strategy used in order to design and implement the sequence of educational activities, leading to a final optimised didactic sequence that was tested in a pilot study. The main results were obtained from the experimentation with several classes in two high-school technical institutes with a chemistry and material sciences curriculum, along with a group of undergraduate students during the first part of an introductory course on molecular spectroscopy.

Keywords: didactic sequence; reflection; refraction; interference; diffraction; emission; absorption; high school; spectroscope; spectroscopy; topic-specific pedagogical content knowledge

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1. Introduction

Spectroscopy is a fundamental part of modern chemistry, and ultraviolet–visible (UV–Vis) spectroscopy is usually introduced at the high-school level [1]. In high schools with technical and/or scientific education curricula [2], UV–Vis spectrometers are key equipment [3]. Nevertheless, UV−Vis spectroscopy is the most accessible type of spectroscopy in almost all high schools, as compared to Fourier-transform infrared (FT-IR) and nuclear magnetic resonance (NMR) spectroscopy. Moreover, it is a powerful way to introduce the basic principles of spectroscopy, since it makes use of the visible region of the electromagnetic spectrum, which is strongly relevant to students' everyday life experiences [4,5]. The accessibility of UV−Vis spectroscopy is also related to the fact that, in the absence of traditional spectroscopic instruments at schools, it is possible to let students build their own instruments, as along with homemade colorimeters [6,7] and homemade spectrophotometers [7–10].

Light–matter interaction is a fundamental topic in chemistry; however, high-school students often find it difficult to understand, as reported in some papers [11]. In fact, light–matter interaction is regarded as one of the most difficult topics for high-school and undergraduate (or post-secondary school) students, since it is usually described as abstract, hard to learn, and taught at school in an excessively theoretical way [12,13]. The emission and absorption of light that are behind the atomic and molecular spectra typical of chemical substances are among the most evident results of the quantum nature of matter; for instance, the patterns of coloured lines in atomic emission spectra are directly related to the electronic structure of chemical elements. Furthermore, quantisation of energy is a fundamental concept to understand the periodic properties of chemical elements and to deeply understand the periodic table of elements. To learn the principles of emission and absorption of light and the basic molecular phenomena behind UV–Vis spectroscopy, students need to be introduced to the nature of light and to its main phenomena, such as reflection, refraction, interference, diffraction, light diffusion, and so on [14]. These fundamental phenomena are not considered properly in chemistry courses, and in some types of high schools they are not introduced at all. In Italy, for instance, in high schools with a technical/scientific curriculum, light phenomena and related concepts are introduced during physics lessons, at the beginning of optics lessons, without any concrete connection to chemistry [15]. A recent educational research paper in physics reported evidence of a low understanding of light phenomena at the high-school level [16]; according to the authors, this low understanding is connected to the lack of instructional tools and strategies used by teachers that could help students to visualise optical and light phenomena. In high-school lessons, physics teachers typically attempt to explain these phenomena in a theoretical way [16], without experimental observations, whereas they should present them in a more visual way—for instance, by taking advantage of external sources, such as YouTube videos, computer simulations, and open-access software. A more interactive and experimental approach could help students in observing and interpreting light phenomena [16]. As discussed in the present paper, these aspects are very important for a complete understanding of light–matter interaction and UV–Vis spectroscopy [17].

In Italy, there are several types of high schools, with different curricula depending on the professional and educational profile. Among Italian high schools, technical institutes with chemistry and material science curricula aim to train future skilled workers in the chemistry-related fields, such as in chemical, biochemical, and medical laboratories, or in chemical plants [18]. Students with a diploma obtained from technical institutes with chemistry and material science curricula usually receive a solid education in chemistry, opening the possibility to access graduate studies in chemistry and related subjects. In fact, during the last three years of the chemistry curriculum (corresponding to levels K-10, K-11, and K-12) [18], students learn advanced topics in all fields of chemistry, which are quite similar to those of the first introductory chemistry courses at the undergraduate level.

In this context, UV–Vis spectroscopy is employed as a fundamental instrument for quantitative chemical analysis. This topic is typically taught in the second year of the chemistry curriculum (IV class, which corresponds to the K-11 level) during analytical chemistry lessons. Spectroscopy is indeed only introduced as a basic technique for very specific applications, such as routine analyses of water [19], oil [20], milk [21], wine [22], and soils. Students rarely learn the fascinating phenomena related to the nature of light and light–matter interaction, such as diffraction patterns and rainbow-like spectra. As a consequence, students usually have a low or superficial understanding of the spectrometers and their optical components, such as the monochromator, the light sources, and so on. Optical phenomena are briefly introduced at the beginning of spectroscopy lessons only at a theoretical level, without laboratory experiments. The laboratory, which is very important in technical institutes, is mostly a place to teach chemical techniques and analytical methods to be applied to real and practical problems. Teachers usually tend to assess laboratory activities via a laboratory report, with the main goal being to evaluate the practical skills [23]; however, as addressed by Seery [24], other goals—generally referred as the pedagogical goals of laboratory works—should be carefully evaluated.

Recent international scientific studies about learning and teaching spectroscopy at the high-school level have focused on analysing the extent of active involvement of students in laboratory activities and, in particular, on "do-it-yourself" spectrometers, which include the use of digital tools and smartphones [7,25]. By analysing the scientific literature in this field, the main educational and conceptual objectives of the research can be summarised as follows:

(1) To avoid the "black-box" approach to spectrophotometers and similar instruments [26];
(2) To make instruments more accessible for high-school teachers (and less expensive) [3];
(3) To increase the versatility of the spectroscopic instruments [7];
(4) To use a multidisciplinary approach to teach spectroscopy—for instance, by adopting the science, technology, engineering, and mathematics (STEM) approach [27].

In the scientific literature, there are only a few examples [1,3,7] of studies centred on the introduction of spectroscopy at the high-school level; moreover, none of them are focused on the didactic sequencing of activities designed and optimised for specific key concepts of spectroscopy. The main purpose of the present study was to develop a new way to introduce spectroscopy to high-school students by constructing a new structured didactic sequence. This is the result of a long experiment with high-school students and with high-school teachers, with the aim being to choose the best sequence of contents and related concepts to help students better understand the basic principles of spectroscopy. To this end, the knowledge of the chemistry contents in high-school curricula is a fundamental starting point, as already underlined by Johnstone [28], who wrote that "*some chemistry content will have to be removed from high school curriculum, some topics will have to be reduced and some topics will have to be rescheduled*" in order to achieve meaningful learning.

The pedagogical framework of our research refers to the pedagogical content knowledge (PCK) theory [29]. In his seminal work, in the mid-1980s, Shulman [30] introduced the idea of pedagogical content knowledge (PCK) as an important category used to guide the pedagogical reasoning employed by teachers in transforming the content knowledge of a lesson for effective learning. He stated that "*comprehended ideas must be transformed in some manner if they are to be taught*", and he defined pedagogical content knowledge as "*the capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful*". Indeed, PCK develops when a teacher finds new ways of explaining difficult concepts. It includes the teacher's understanding of the important concepts and sequencing of concepts of the topic, and of how specific topics are organised and presented for instruction. Research studies on PCK have measured this knowledge and its role in teacher preparation programmes [31,32]. PCK applied to teacher preparation programmes is useful in understanding teachers' knowledge. Moreover, PCK is a theoretical framework through which science education researchers can conceptualise and evaluate the necessary professional knowledge of expert teachers. It is commonly accepted that PCK has a topic-specific nature [33–37], rather than referring to a subject or to a discipline.

In order to make explicit the development of PCK within a specific topic, components that enable the transformation of subject matter knowledge to PCK were identified [35–37] within the topic-specific pedagogical content knowledge model (TS-PCK) as *learners' prior knowledge*, *curricular saliency*, *what makes a topic easy or difficult to understand*, *representation*, and *conceptual teaching strategies* (see Figure 1).

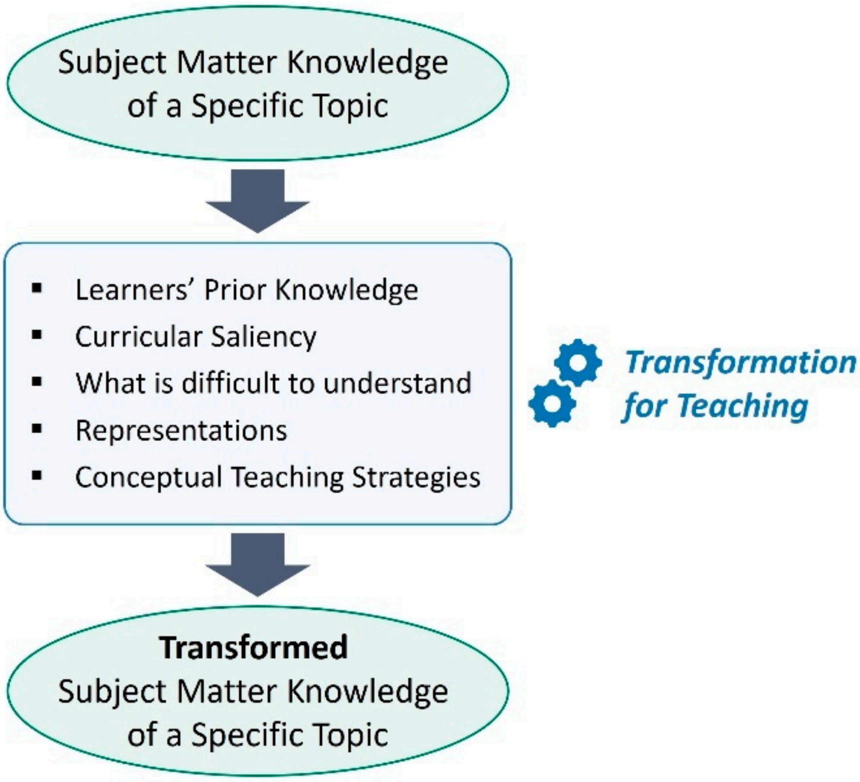

Figure 1. Process of transformation of subject matter knowledge for teaching in the TS-PCK model [35–37].

In this work, we utilise the TS-PCK theoretical framework to investigate and characterise the topic-specific pedagogical content knowledge related to light phenomena, which are the basis of the understanding of UV–Vis spectroscopy. In other words, our aim is to propose how to present concepts of light properties and introductory concepts of UV–Vis spectroscopy, formulating the sequence of educational activities into a version suitable for high-school learners.

In the present study, the TS-PCK model is used to develop the transformation of the subject matter of a difficult topic, i.e., light–matter interaction and spectroscopy. The research presented in this paper was developed by a team of researchers and high-school teachers. In particular, a high-school teacher developed and tested this research during her PhD thesis on chemical education, an undergraduate student contributed to this research during her master's thesis on chemical education, and a university professor of spectroscopy and chemistry education within a research project and a high-school teacher developed new STEM laboratories for spectroscopy and tested them with high-school students. The structure of the present research paper is as follows: after the Introduction (Section 1), the methodology, the description of the participants and the materials, and the evaluation and assessment are reported in Section 2 (Materials and Methods). The proposed and experimented didactic sequence (light phenomena and historical introduction to the spectroscope) is described in Section 3 (Results), and the final Discussion is presented in Section 4.

2. Materials and Methods

2.1. The Theoretical Framework and the Methodological Approaches

The aim of this research was to develop a didactic sequence to introduce spectroscopy in high schools, and to test it on high-school students. During this work, we referred to the content-specific components of the TS-PCK pedagogical model, which helped us in better analysing the students' reasoning according to the constructivist approach [38]. The constructivist approach is important to help researchers in achieving the transformation of subject matter knowledge that is necessary to build an effective didactic sequence. A fundamental aspect of the constructivist method is the examination of students' reasoning and learning. In this pedagogical framework, the "meaning" is indeed constructed by students from an experience (e.g., laboratory work, the observation of a phenomenon, etc.), and the teacher/researcher can see how each student views a subject or a phenomenon and how they elaborate an explanation of the observed phenomenon. Within the TS-PCK model, the teachers/researchers are able to gain a deeper understanding of how students think and learn with respect to a specific subject, and to determine students' cognitive obstacles [38]. Based on this theoretical model, we developed a five-step teaching strategy, which was defined and optimised during our research and experimentation with students. In particular, this five-step structure was used for each activity (laboratory, lessons, didactic activity, etc.), and it was very important for the optimisation of the didactic sequence to introduce spectroscopy to high-school students (see the green blocks in Figure 2). The five steps of each activity of the proposed didactic sequence are as follows:

(1) ***Observation:*** A phenomenon is presented by an experiment, and students observe it.
(2) ***Description***: Students are required to describe and to draw the observed phenomenon by filling in a form (see, for instance, some examples in the Supplementary Materials). This work helps students to recognise the basic features of a phenomenon and promotes careful and critical observation.
(3) ***Reflection***: During a lesson or an activity, the teacher comments on the students' answers and the contents of the description forms in a collective discussion with all students. During this step, an inquiry-based learning process starts. For instance, during this step, the teacher can use a digital tool to present the critical issues that emerge in the "Description" forms. A collective discussion usually starts from controversial aspects or different answers given by students to specific questions. According to the constructivist approach, these controversial aspects should induce students to critically re-elaborate their initial ideas, encouraging questioning and modelling of what they saw and understood during the observation step. After this collective reflection, students are required to fill in a "reflection form" (see some examples in the Supplementary Materials). This is an important part to promote students' self-reflection on phenomena and their explanations of them.
(4) ***Explanatory***: After a careful analysis of the observation forms and reflection forms filled in by students, and after the collective discussion, the teacher identifies the students' cognitive obstacles and critical issues related to the specific concepts addressed during the didactic activity. Based on these, the teacher prepares a lesson to clarify the critical points, so as to explain some new key concepts reorganised in a clearer way.
(5) ***Exploratory***: After the introduction of new concepts in the "explanatory lesson", the teacher proposes a new inquiry-based activity in the laboratory. The aim of this step is to verify a concept or a theory, or to apply it by designing and carrying out an experiment.

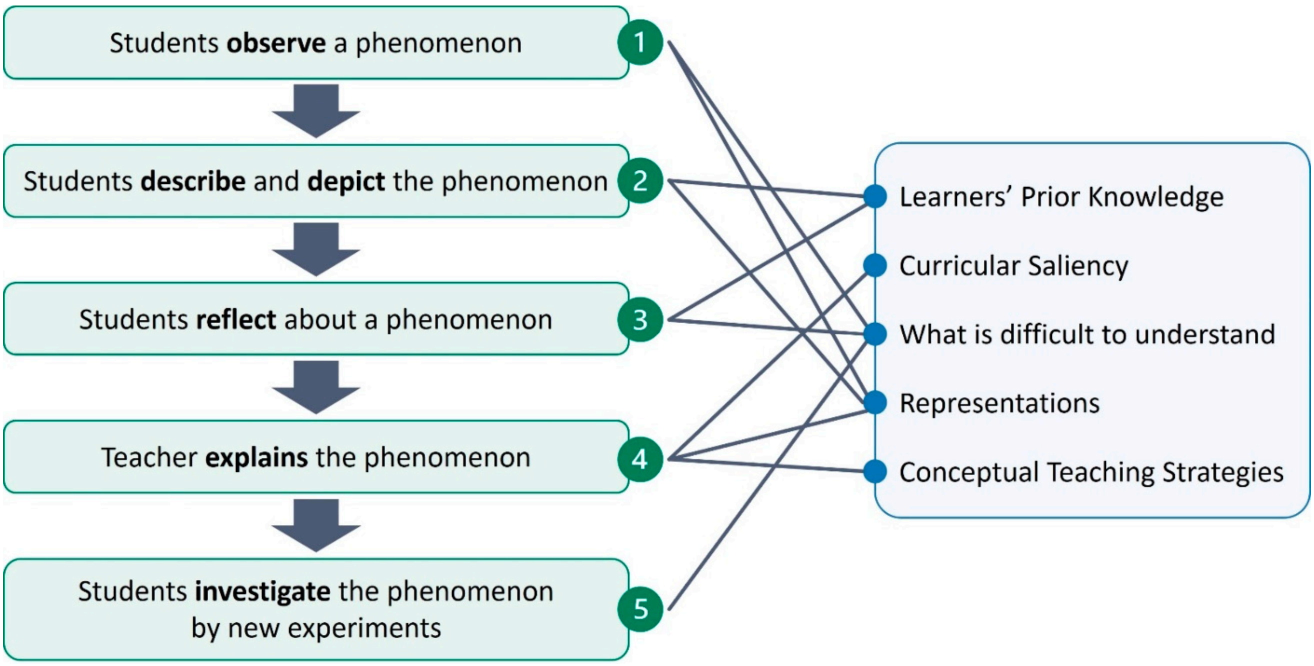

Figure 2. Scheme showing the relationship between the five steps of our approach used to build the didactic sequence (green blocks) and the content-specific components of the TS-PCK model.

Within the didactic sequence optimised during the present research, this five-step structure was used, along with several teaching and learning methods. During the "observation" and "exploratory" steps, active laboratory approaches and digital didactic methods were adopted; for instance, smartphones were used to take photos and videos, while specific software was used to manipulate photos and to analyse them. During the "observation", "explanatory", and "exploratory" steps, the historical–epistemological approach [39] was utilised to introduce some specific topics. In particular, the reproduction of historically relevant scientific experiments (such as the Young experiment) and the use of real historical instruments used in experiments (such as the historical Kirchhoff–Bunsen spectroscope) are concrete examples of how the historical educational approach was used at the high-school level in our study. Within the "exploratory" step, inquiry-based laboratory activities were designed and performed with students.

As described above, our research refers to the TS-PCK model. In fact, each of the five steps proposed in our approach can be correlated to one or more *content-specific components* according to the TS-PCK model (Figure 2).

2.2. The Participants

The whole didactic sequence was implemented over the course of several years, and it was optimised in a pilot project that involved three classes at two different chemical technical institutes, indicated herein as class 1, class 2, and class 3. The chemical technical institutes are the Istituto di Istruzione Superiore "Galilei-Sani" in Latina (Latina, Italy) [40] and the Istituto Tecnico "C. Cattaneo" in San Miniato (Pisa, Italy) [41]. The first experiment was conducted in the period between October 2020 and November 2020 with classes 1 and 2 at the Institute "C. Cattaneo"; students of these classes attended the third year of the chemistry and materials curriculum (corresponding to K-12 level). A second experiment was conducted in the period between October 2021 and March 2022 with the students of class 3 at the Institute "Galilei-Sani" attending the second year of the chemistry and materials curriculum (corresponding to K-11 level). Class 1 was made up of 16 students (5 females and 11 males), class 2 contained 17 students (7 females and 10 males), and class 3 contained 22 students (8 females and 14 males).

The didactic sequence was implemented during analytical chemistry and laboratory lessons [18]. In particular, the first experiment in classes 1 and 2 covered a total of 12 h divided across four days (3 h per week), while the second experiment was carried out over a longer period, during the analytical chemistry and laboratory lessons (7 h per week) in class 3. These lesson hours included laboratory activities, which represented about 60% of the total hours.

A third experiment was carried out during laboratory lessons of a physical chemistry course during the second year of the undergraduate course in industrial chemistry with environmental chemistry at the University of Pisa [42]. The course presents a first part dedicated to the introduction of spectroscopy, and the topic "the nature of light and light phenomena" is explored during 15 h of theoretical lessons and about 5 h of laboratorial activities. This third experiment was performed in the periods of March–April 2021 and March–April 2022, with a total of 53 students (55% were female).

2.3. Materials

"Observation" and "reflection" forms were prepared and given to students of the three classes at the chemistry technical institutes. Some examples (translated from Italian to English) are reported in the Supplementary Materials. In addition to the didactic laboratory equipment and substances needed for the laboratory activities, others materials were utilised, including red and green laser pointers (3B Scientific Green Laser Module U22001 Red Laser Diode, 650 U22000), diaphragms with single, double, and multiple slits and gratings (3B Scientific diaphragms: U8476600 with single slit and double slits, U14101 with double slits, U14102 with multiple slits and grating; Edmund Optics linear diffraction gratings 500 lines/mm and 1000 lines/mm, Diffraction Grating Slide Holographic Linear 500 lines/mm Lamp Laser Spectrum), an adjustable slit (3B Scientific Adjustable slit K U8476675), flat mirrors, a didactic spectroscope (Leybold-Heraeus), denatured alcohol, sugar, dry ice, and an interactive whiteboard.

2.4. Assessment and Evaluation

The high-school students were evaluated by a final test composed of open-ended questions for each topic and activity. In addition, *in itinere* examination texts (oral and/or written) were adopted by the teacher. However, in this paper, we do not report the final evaluation of the students' knowledge, since the focus is the description of the methodology adopted to build the didactic sequence optimised to introduce light–matter interaction and light phenomena as the basis of spectroscopy. In order to support and demonstrate the validity of our didactic sequence, we show a selection of the students' feedback. For instance, the most significant results obtained by analysing the "observation" and "reflection" forms are reported and commented on herein. A selection of drawings (see also the Supplementary Materials) is also reported in order to underline the methodology used by the teacher to evaluate the students' understanding of the phenomena. In parallel, some examples of answers to specific questions proposed to students to evaluate their learning are also reported and discussed. Some examples of "observation forms" and "reflection forms" concerning some of the experiences and activities described in the present paper are reported in the Supplementary Materials. The efficacy and levels of engagement achieved by high-school students during the experiments were evaluated via anonymous surveys. Some of the main feedback is reported in the Supplementary Materials. The present pilot study is mainly focused on the presentation and discussion of the optimised didactic sequence, and its efficacy will be investigated in a further work extending the experiment to a larger number of students.

3. Results

As reported in Section 2.2, the first experiment was conducted in October and November 2020 in class 1 and class 2 simultaneously, while the second experiment was carried out from October 2021 to March 2022 in class 3. These two experiments were fundamental to build up and optimise the didactic sequence. A visual pathway of the final didactic sequence optimised during this research—including the development of a new teaching strategy and the experiments with the students—is reported in Figure 3.

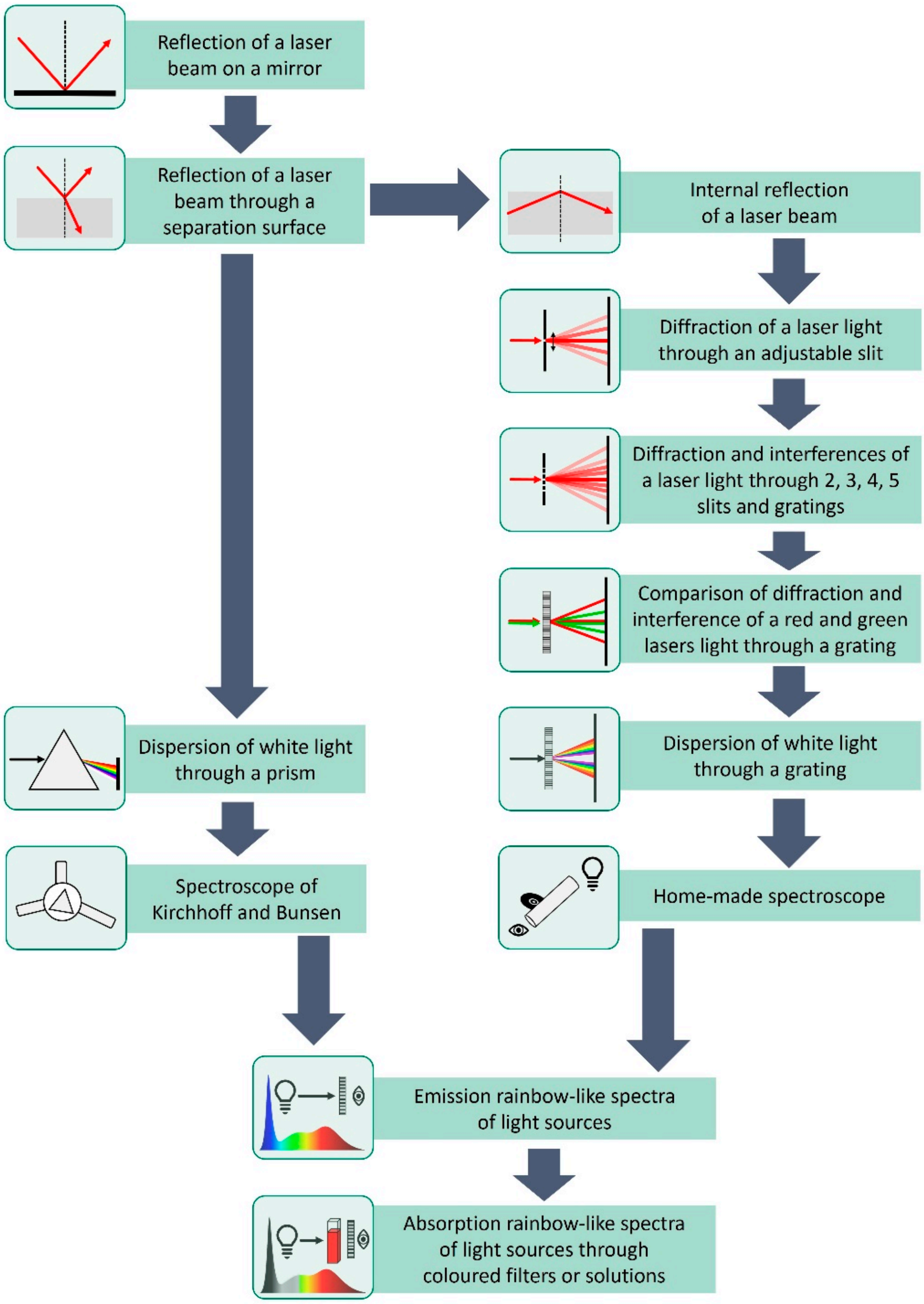

Figure 3. Visual pathway of the didactic sequence obtained as a result of our conceptual teaching strategy.

The first experiment with the students was focused on the development of the activities related to the topics of reflection and refraction of light. Diffraction and interference phenomena of light, along with the principles of spectroscopy, were introduced to students of class 1 and class 2. However, the design and optimisation of the didactic activities dealing with these topics was limited due to the blended teaching mode ("presence-distance") that was adopted during the COVID-19 emergency. For instance, the students of class 2 were mostly learning remotely, so the practical work—such as the STEM laboratory activities—could not be performed. Nevertheless, during the first experiment, educational videos concerning light properties such as reflection, refraction, diffraction, and interference were presented to help student learning [43–46]. Moreover, a large amount of documents and interactive materials were made during the first experiment, and they were collected on a website named DAD-Spectroscopy [47], which was specifically created by two of the authors to share useful educational materials with Italian teachers during the COVID-19 pandemic. These materials and the feedback from Italian teachers were useful in the development and optimisation of the didactic sequence reported in this paper.

The second experiment was conducted with a single class of students over a long period (about 5 months), and it was helpful in developing and optimising the part of the sequence concerning the diffraction, interference, and dispersion of light, as well as to design and test the activities involving the spectroscope. During the second experiment, the educational videos made during the first experiment and some of the materials prepared during the COVID-19 pandemic [47] were used in class to test their educational efficacy.

Furthermore, the second experiment was used to implement some aspects of our research methodology, such as the evaluation of students' learning and pedagogical reasoning, as discussed in the next section.

The third experiment [48], conducted with undergraduate students, did not follow the five-step teaching strategy, since the structure and timing of lessons and laboratories at the university do not allow that. However, this experiment was helpful to implement the experiments concerning the diffraction, interference, emission, and absorption phenomena, as well as to check the possibility of transferring some parts of the didactic sequence shown in Figure 3 from the high-school level to the undergraduate level.

In the following paragraphs, some of the key aspects of the didactic sequence presented in this paper are described and discussed. Some examples of activities performed with students by using different teaching methods are described in detail, and the most significant aspects from the learning and teaching points of view are discussed.

3.1. Light Phenomena

Light phenomena, such as reflection and refraction, were presented through experiments that can be easily set up in high-school laboratories (Figure 4), e.g., the reflection of red or green laser pointer beams on a flat mirror on a wall, the refraction of a red laser pointer beam through the interface between air and an aqueous sugar solution, and the internal reflection of a red laser pointer beam at the interface between a water–alcohol solution and air (observation step).

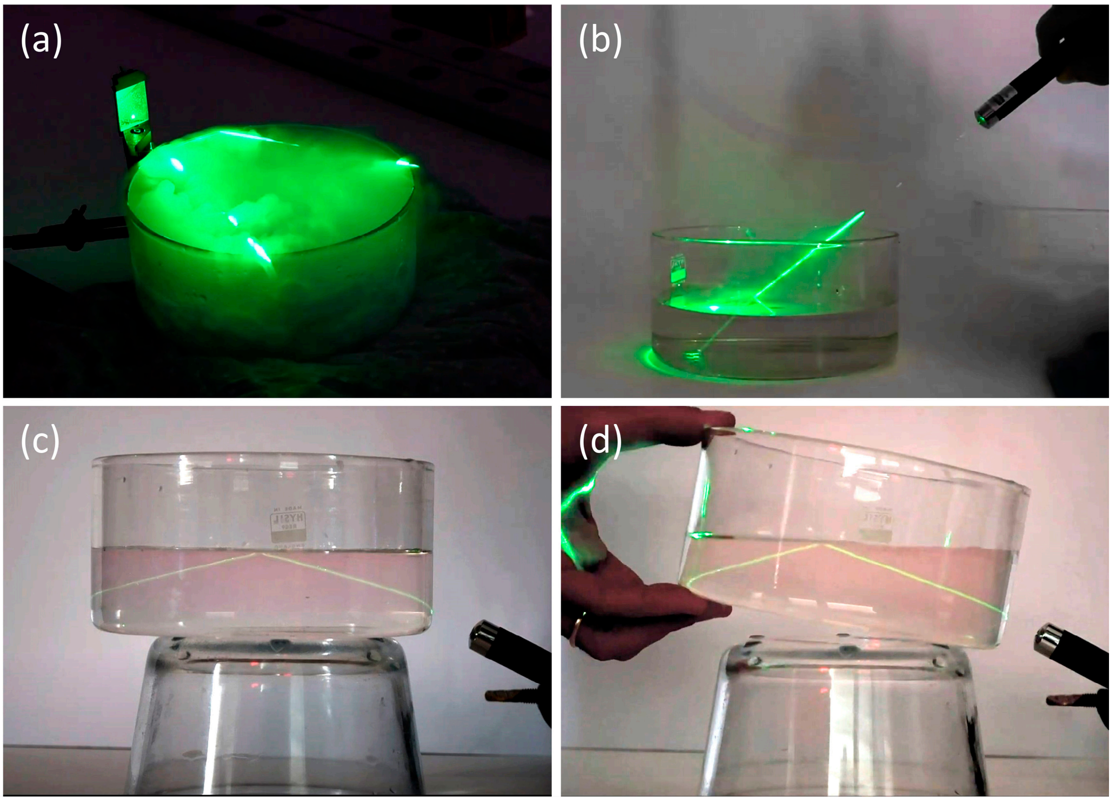

Figure 4. Snapshots taken from the didactic videos made during the first experiment [33–35]: (**a**) reflection, (**b**) refraction, (**c**,**d**) internal reflection.

The optical path of laser pointer beams in solutions could easily be visualised by students through these experiments (see Figure 4). In air, it is possible to see the optical path thanks to the scattering of light by means of dispersed microparticles—for example, those produced by dry ice sublimation, powder rubbed with a brush, or other simple methods. During the first experiment with the students of class 1 and class 2, several videos were produced to help the students during remote lessons. In this case, the beam path was highlighted by digitally superimposing coloured lines to help students to visualise it (for instance, see [34,35]). After the observation of the three experiments, students had to fill in an "observation" form (reported in the Supplementary Materials), where they were asked to describe the phenomenon and to represent it with a drawing (*description step*). The schemes and representations helped the students to recognise the geometric features of the beam path, which are very important in optical phenomena, while describing the phenomena in writing and answering specific questions promoted the students' metacognition. After these steps, the descriptions and drawings provided by the students were analysed by the teacher in order to understand the students' previous knowledge and eventual difficulties in visualising the phenomena. Then, the teacher shared the results and the outcomes from the completed forms and led guided discussions among the students. Thereafter, the students were required to fill out a second form (*reflection step*). During this activity, the students had to think about specific features related to the observed phenomena, such as the straight propagation of light beams or examples of these phenomena in everyday life.

The students' answers were analysed by the teacher in order to understand the students' reasoning and to identify cognitive obstacles. The *explanatory step* of our methodology included a theoretical lesson about the observed phenomena. Optical phenomena, such as reflection and refraction, are very important to understand how optical components work inside a spectrophotometer and how the decomposition of light into its constituents (i.e., colours) takes place.

The next optical phenomena of the didactic sequence were diffraction and interference, which are related to the "wave nature" of light—a challenging task for high-school students [11]. The wave nature of light is not simple to understand, since it is not associated with a visible property of light and it is not intuitive. In contrast, as explained above, reflection and refraction are related to the particle nature of light, which can be associated with something visible: the laser beam. The theoretical explanation of the interference and diffraction phenomena requires mathematical concepts and tools that are not usually taught at the high-school level—especially in technical institutes. In our didactic sequence, these two phenomena were introduced with an interactive STEM laboratory approach. Since all modern instruments use a diffraction grating to disperse light into its components, our teaching goal was focused on the phenomenological understanding of the basic principles of light's dispersion through the diffraction gratings. For instance, a sequence of experiments was proposed by using red or green laser pointer beams with several diaphragms with an increasing number of slits (from 2 to 40, as shown in Figure 5).

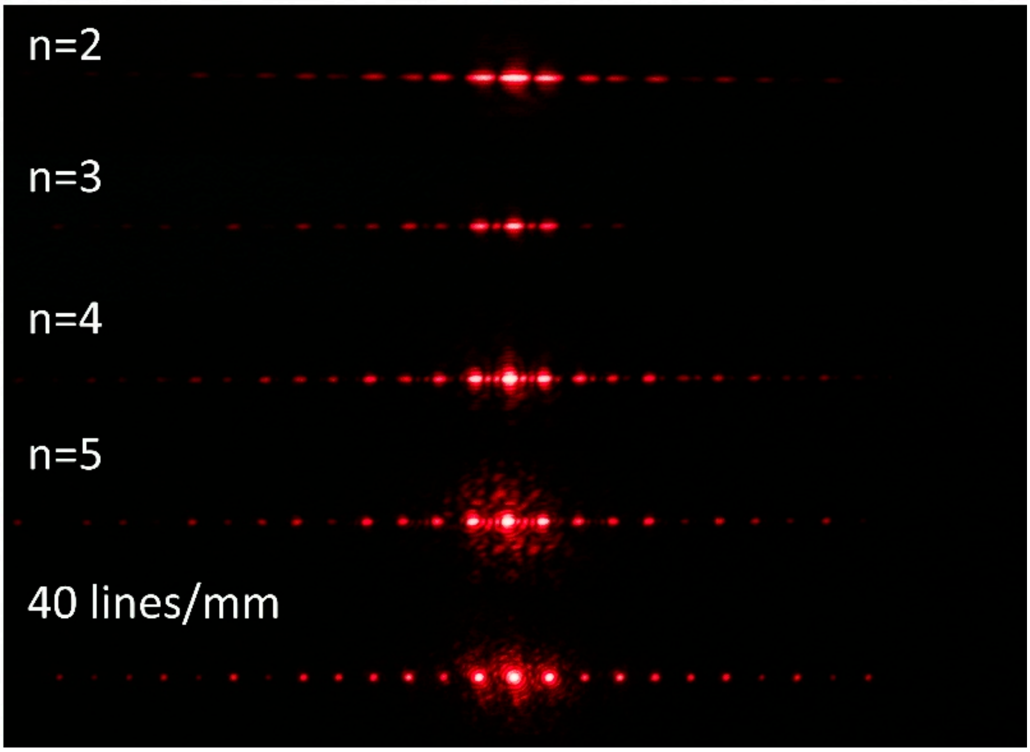

Figure 5. Photos taken by students showing the diffraction patterns observed through 2, 3, 4, or 5 slits, and through a grating with 40 lines/mm.

A sequence of experiments was proposed to help students understand how diffraction patterns form and how they change when changing relevant parameters, such as the size of the slits and the number of slits. The sequence of experiments optimised during the second experiment was as follows:

(1) An adjustable slit can be used to explore two limiting situations: (a) if the slit width is much bigger than the wavelength of the laser (i.e., 2–3 mm), no diffraction is observed; (b) if the slit width is very small and it can be approximated to a point source (i.e., a few microns), no diffraction is observed. All intermediate situations give rise to a diffraction pattern. Indeed, students can observe the appearance of diffraction fringes when the width of the adjustable slit is of the same order of magnitude as the wavelength.

(2) Diaphragms with a single slit of a known width (commercially available, as reported in Section 2.3) can be used to show how diffraction patterns change by changing the slit width.

(3) Diaphragms with double slits with different known distances can be used to show the phenomenon of interference, which causes changes in the diffraction patterns.
(4) Several experiments with multiple slits (three, four, and five slits) can be performed to show how the fringes change in their intensity and shape due to the increasing number of slits (see the diffraction patterns in Figure 5).
(5) Different diffraction gratings (i.e., with 40, 80, 100, 500, and 1000 lines/mm) can be used to show the relationship between the number of lines/mm of the diffraction grating and the distance between the maxima of the intensity of the diffraction fringes.
(6) By using a diffraction grating with 500 or 1000 lines/mm, a similar experiment can be conducted using two lasers, such as red and green laser pointers, projecting the diffraction pattern at the same time. This experiment is very effective in showing the effects of different wavelengths on the diffraction patterns (for instance, see the zero and first orders of diffraction in Figure 6).

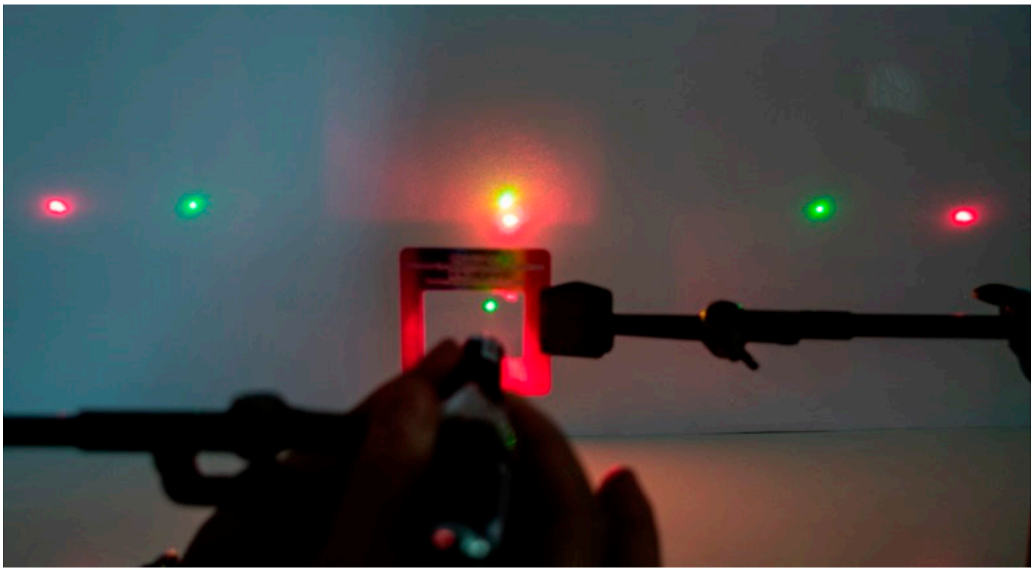

Figure 6. Snapshot taken from the didactic video [46] showing the diffraction pattern of a red and a green laser beam through a diffraction grating with 1000 lines/mm.

This didactic sequence shows the evolution of a diffraction pattern, which is very important for students to understand how a diffraction grating works and, in particular, gradually introduces the students to the phenomenon of dispersion of light and to the special separation of the different coloured components. As for the reflection and refraction topics, as in the case of the interference and diffraction phenomena, the five steps of the teaching strategy were used: the “observation step” (as shown in Figures 5 and 6), “description step” (with the help of forms, as reported in Figure 7), “reflection step”, “explanatory step”, and “exploratory step”.

1- Laser beam through multiple slits

Laser beam passes through multiple slits on a diaphragm. An image of light is projected on the wall or on the board. Student after carefully reading the characteristics of the diaphragm, shown below, and after observing the phenomenon fill in the form by answering the questions.

Diaphragm has four types of multiple slits with constant distance and width and a grating

Width 0.15mm

Distance 0.20 mm

Number of slits 2, 3, 4, 5, 40

1-How does the image change by changing the number of slits? **a-Represent the projected imagine with a drawing.**	**1-b-Describe the projected imagine.**

Figure 7. Example of the "observation form" (*description* step) delivered to students after the experiments, concerning the diffraction phenomena observed with a variable number of slits and a diffraction grating (shown in Figure 5).

3.2. Introduction to the Spectroscope through a STEM Laboratory Approach

After having addressed the topics of reflection, refraction, interference, and diffraction, the students should know all of the light phenomena and be ready to see some applications of the dispersion of light. The "exploratory step" allows students to explore the dispersion of light by using the two main "optical elements" that are used for this purpose in spectroscopy: the prism, which is based on refraction; and the diffraction grating, which is based on diffraction. The core of this step of experimentation is the activity of the homemade spectroscope. Indeed, the students were required to build their own spectroscope by using available materials and a guide given by the teacher (see the Supplementary Materials), and to use it to observe rainbow-like spectra produced by different light sources (Figure 7).

As shown in Figure 8, the observed spectra can be continuous spectra (as with tungsten or halogen lamps), spectra of lines (as with mercury or sodium lamps), or relatively large-band spectra (as with LED-type lamps). During the COVID-19 pandemic, the students built their own homemade spectroscopes by using materials available at home (such as a DVD as a diffraction grating). Then, the students chose several light sources (e.g., light emitted by their smartphone, home lightbulbs, LEDs, candles, etc.). As shown in the "guided form" reported in the Supplementary Materials, they were asked to take photos of the observed spectra (see some examples in Figure 8) and to fill in a form with the description of their instrument, light sources, photos of the spectra, and other comments.

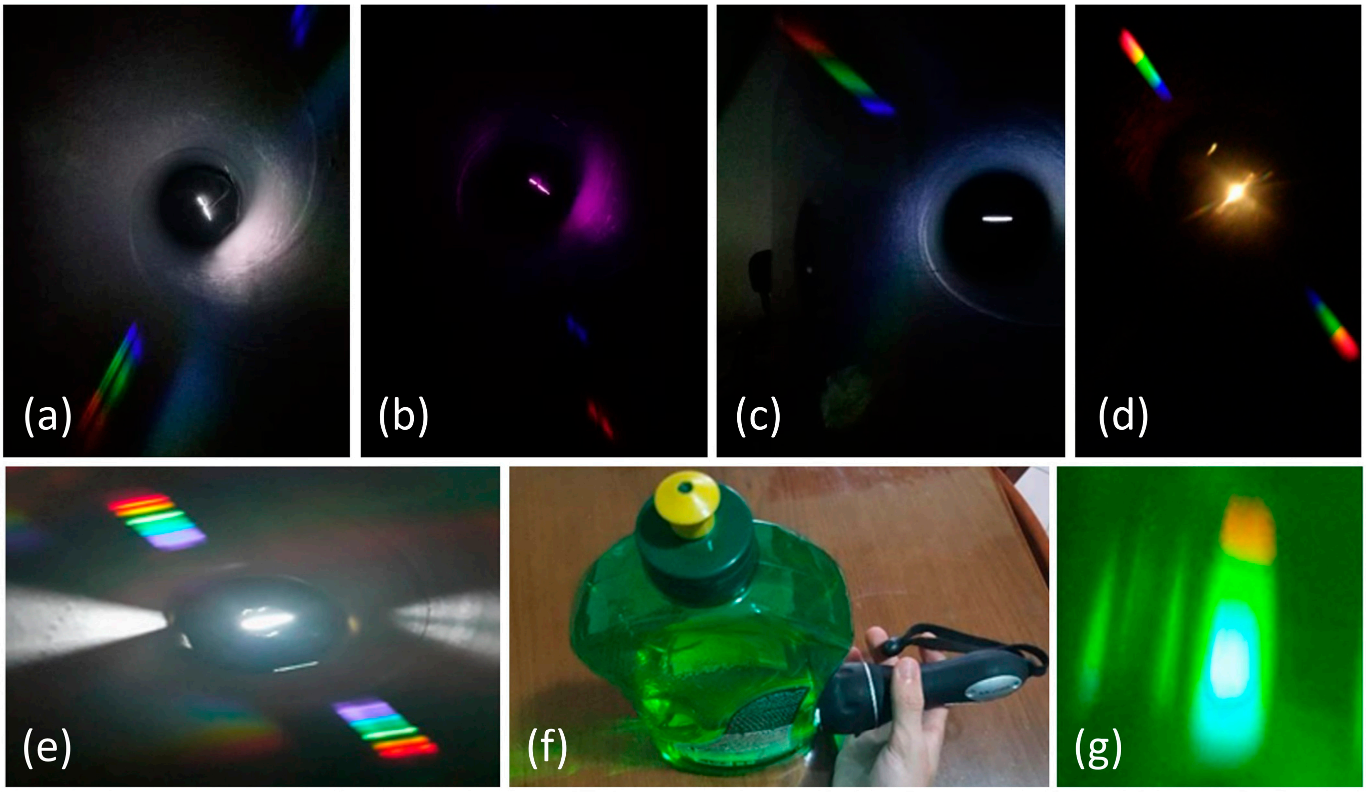

Figure 8. From top left to bottom right, photos taken by students of rainbow-like spectra produced with homemade spectroscopes: (**a**) white LED; (**b**) purple LED; (**c**) white page of a Microsoft Word document on a PC; (**d**) candle flame; (**e**) home lamp; (**g**) absorption spectrum of a white flashlight through a green soap solution (**f**) made by a student.

This part of the didactic sequence is based on an integrated educational approach, typical of STEM (or STEAM) laboratory activities. Moreover, digital tools such as open-access software were used to elaborate the coloured spectra and, in some cases, students were able to obtain the emission spectrum (intensity versus wavelength) from the coloured spectrum.

The activity based on the building of homemade spectroscopes was also performed in the subsequent years, even though the lessons were mostly conducted in person, since student feedback was very positive at the high-school and undergraduate levels (see also the Supplementary Materials) [47]. The forms filled in by the students were analysed and evaluated, and they contributed to the final vote. In the Supplementary Materials, the original form with instructions given to students to build their homemade spectroscope, the reflection form, and the scheme used for the students' evaluation are reported.

3.3. The Historical Approach to Introduce Spectroscopy

The history of spectroscopy started with Newton's famous experiment of dispersion of solar light by means of a quartz prism, and his detailed explanation thereof. The observations of bright colours produced by some salts in a flame by several scientists during the 18th century further contributed to the beginning of a new field of science—namely, spectroscopy. The observation of rainbow-like emission spectra of different elements placed in a flame, and the historical steps that led to the assembly of the first spectroscopes from different optical components (such as slits, mirrors, and diffraction gratings), —are very significant from an educational point of view.

In most cases, the study of spectroscopy at the high-school level starts with the description of the spectrophotometers, which are typically presented as modern instruments. However, historical instruments such as the Kirchhoff–Bunsen spectroscope (Figure 9) are very important from the educational point of view. First of all, students can more easily understand how the spectroscope works, since it is relatively simple compared to spectrophotometers. By using a spectroscope, students can observe rainbow-like spectra, which are easier than emission and absorption spectra. Furthermore, the comparison between the historical spectroscope and the homemade spectroscopes built by students—as reported in the previous paragraph—represents an interesting activity, where an integrated approach between a STEM methodology and a historical approach usually brings high levels of engagement and stimulates students' participation, as recently demonstrated in a training course for future chemistry teachers [49,50]. The parallels between the Kirchhoff–Bunsen spectroscope and the homemade spectroscope help students identify the similarities and differences in terms of optical components and can help them in consolidating the principles of the spectroscopes' function.

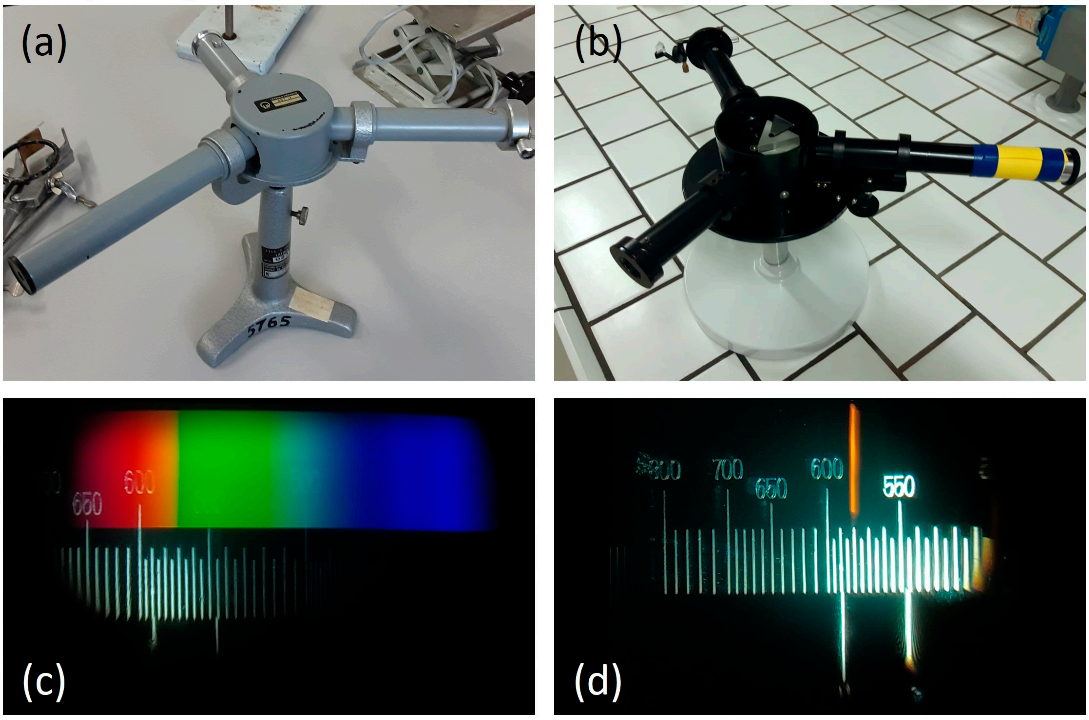

Figure 9. From top left to bottom right, (**a**) modern and (**b**) old Kirchhoff–Bunsen spectroscopes used during the first and second experiments; example of a (**c**) continuous spectrum and (**d**) sodium lamp line spectrum obtained with the modern spectroscope during the second experiment.

In this pilot study, the historical approach was not restricted to historical instruments such as the Kirchhoff–Bunsen spectroscope, but was extended to some aspects of the theory lessons; for instance, the so-called Kirchhoff's three laws of spectroscopy and their explanations were introduced during theory lessons by using a historical approach. In all cases, the use of a historical method has the aim of helping students to contextualise scientific laws and to understand the role of both theory and technical advancements in science [39,51,52]. The historical approach can promote different educational goals, as reported in the literature [39,51,52]; it promotes questioning, while traditional approaches too often supply only answers [51]. Historical approaches tend to put the experimental horse before theoretical cart [51], recognising imagination [51], while also fostering habits of thinking [52] by showing how great scientists drew their conclusions and how their minds worked in the process. In the specific case of spectroscopy, our experiences over the years confirm that the historical approach helps students in better understanding the key concepts at the basis of modern instrumentation.

4. Discussion

In this part of the paper, we present evidence of how our methodology and final didactic sequence for the introduction of spectroscopy at the high-school level can be correlated with the content-specific components of the TS-PCK model. This theoretical framework helped us in determining how to transform "subject matter knowledge" into a form suitable for teaching and learning spectroscopy. Several considerations were taken into account before (planning), during (teaching), and after (reflection) the implementation in the classrooms, and the most relevant conclusions are summarised in Table 1.

Table 1. Final considerations concerning the didactic sequence described herein to introduce spectroscopy at the high-school level, through the content-specific components of the PCK model.

Content-Specific Components	Final Considerations and Main Aspects of the Didactic Activity for the Introduction of Spectroscopy at the High-School Level
Learners' prior knowledge	(1) Light is seen as made of straight rays and not of waves; (2) The concept of waves is not clear to almost all students; (3) The origin of colours is unknown, and not all students know that white light contains all colours of the rainbow together.
Curricular saliency	(1) Reflection, refraction, and diffraction phenomena are relevant in order to understand how light is guided and dispersed inside spectroscopic instruments; (2) Emission and absorption are real phenomena behind the absorbance algorithm.
What is difficult or easy to teach	(1) Equations used to explain optical phenomena, such as interference and diffraction, are too abstract and require mathematical tools that are not accessible to all students; (2) The wave nature of light is particularly hard to teach; in fact, learners cannot visualise the wave aspects of light; (3) Interference and diffraction are combined phenomena that take place at the same time in most of the real cases; the Huygens–Fresnel principle cannot be proposed to high-school students; (4) The absorbance, which learners usually read on the digital interface of an instrument, is associated with an algorithm of light intensity, which is the real measured quantity.
Representations	(1) The visual representation of the concepts by approaching them with experiments (macroscopic or phenomenological level) is important for the learners, and it is a more direct and effective teaching approach; (2) Real images (i.e., photos and videos) of reflected, refracted, diffracted, emitted, and absorbed light are used instead of plots and graphical representations.
Conceptual teaching strategies	A visual pathway is an interesting conceptual teaching strategy, and this aspect was optimised and used in the research approach described in this work.

As summarised in Table 1, *what makes these topics difficult* are the mathematical laws behind the phenomena, the concept of waves and related equations, and the use of abstract representations and plots. *Representations* are strongly related to *what makes these topics difficult or easy* in the specific topic of light phenomena and spectroscopy. *What makes these topics difficult* suggests critical ideas in *curricular saliency. Curricular saliency* focuses on the most important concepts of the topic, critical ideas that connect concepts among them, and their role in the students' understanding. The critical ideas represent the starting point of our research: the role of light phenomena is of great importance to understanding how a spectrophotometer works. *What makes these topics difficult* is the Huygens–Fresnel principle, which instructors cannot teach to high-school students, since it is very complicated due to the mathematical tools involved. The following critical ideas emerged during the experiments: (1) The wavefront passing through a single slit broadens, and then waves from the slit interfere with waves from the other slits. (2) Waves from each of the two slits interfere in a constructive and destructive manner; students need knowledge about the geometric relationship between pathlength difference and wavelength. (3) The presence of dark and bright fringes obtained with double slits can be explained in terms of constructive and destructive interference. *What makes these topics easy* is the visual representation of light phenomena, e.g., the reflecting or refracting light rays, the rainbow-like emission spectra of a light source, the rainbow-like absorption spectra of a light source, etc. Visual experimental representations are easy to understand; moreover, video and digital materials are very useful in case experiments are not possible at school.

The differences between emission and absorption spectra can be easily understood if students are first introduced to Kirchhoff's spectroscopy laws and spectroscope experiments with different light sources and filters. In fact, in more traditional lessons, absorption and emission spectra are perceived as abstract concepts.

Furthermore, *what makes this topic difficult* emerges from the level of detail of the experimental activities. Indeed, some experiments of the didactic sequence (as shown in Figure 3) can be relevant at the undergraduate level, but they might produce cognitive overload [53–56] at the high-school level. This is the case of the sequence of experiments with single slits of different widths and with multiple slits.

These experiments are useful to understand the behaviour of diffraction patterns and interference patterns when separately changing the distance and width of the slits. During the third experiment involving undergraduate students [57], the convoluted diffraction and interference patterns were simulated by student using a Python program [58] developed by one of the authors.

The simulation of the diffraction patterns allows the students to better understand the effects of interference and diffraction phenomena on the final image, and to analyse how the patterns change with the variation in some parameters. Moreover, the experimentally observed pattern can be easily compared with the results of the simulation (see a student's report in Figure 10). However, at the high-school level, similar activities may be too complicated. This emerged clearly from the statements of the students in the completed forms during the second experiment. At the high-school level, the relevant issue is how light is dispersed. From our experiences with high-school students, it is sufficient to show the diffraction with a single slit and the interference when using a diaphragm with a double slit, and it is useful to show the trend of patterns from a double slit to a grating passing multiple different slits (as shown in Figure 5) at a qualitative level.

The experiments with high-school students indicated that students do not recognise all aspects of light phenomena during the "observation step"; some students did not observe secondary fringes in the diffraction patterns through multiple slits (see Figure 11a); all students observed that in reflection on a flat mirror the beam comes back, but only a few students noticed that the angle of incidence of the light beam is equal to its angle of reflection. In all classes of high-school students, we noticed that quite a large number of students (from 25 to 55%, depending on the phenomenon) had difficulties in correctly visualising the phenomena. For example, during the observation of the refraction experiment at the interface between a solution and air, not all students correctly represented the refracted and reflected rays (see Figure 11b). Further examples of students' drawings and feedback are reported in the Supplementary Materials.

In addition, high-school students could not describe the relevance of some aspects of the observed phenomena during the *reflection step*. For instance, seeing alternating dark and light spots or fringes when a laser beam passes through a narrow slit was not correctly associated with the wave nature of light. About 65% of the high-school students who participated in this pilot study understood this point only after the teacher's explanation ("explanatory step"), and not during the "reflection step". This is a further confirmation of the difficulty of the concept of the wave nature of light for high-school students. Even if the students saw dark spaces between bright fringes, they usually focused only on the broadening of the light spots, and it was necessary to present a new experiment or to show a didactic video to consolidate their understanding of this concept. Thus, visual representations of the topic through experiments must be skilfully simplified and sequentially organised [59], and the teacher should carefully guide students during observation and reflection. *Learners' prior knowledge* was investigated by the examination of students' statements in the returned forms and in the short prior-knowledge assessment tests that displayed common misconceptions about the nature of light (not reported here). *Consideration of conceptual teaching strategies* was made continuously during the third experiment, which covered a long period (about three years), and the teaching strategies were tested during the didactic sequence.

The constructivist approach was very useful in making content-specific considerations and defining the pedagogical content knowledge of light phenomena when introducing spectroscopy. Finally, some comments can be made concerning the students' engagement: during these activities, the students were seeking explanations continuously; there were no distractions during lessons, whether in the classroom or in the laboratory. Based on the average votes and positive feedback obtained during the experiments, we can state that almost all of the students understood the main concepts at the basis of spectroscopy. Moreover, the STEM laboratory activities reached a very high level of participation and active involvement, stimulating critical thinking in most of the students. In the case of the undergraduate students, the results of a final anonymous survey demonstrated that almost all of the students (46 of a total of 53 students) appreciated the activities and thought that the historical approach was helpful to understand the key concepts of spectroscopy and important for chemists (see Plot S11 in the Supplementary Materials). One limit of the learning by discovery utilised in this study comes from a practical standpoint: its feasibility depends on the time costs involved, which are usually very high. This aspect should be carefully considered at high schools, where students are expected to cover a great deal of subject matter [59]. The visualisation of the didactic sequence from spectroscope to spectrophotometer is an ongoing research project, and it will be the object of future works.

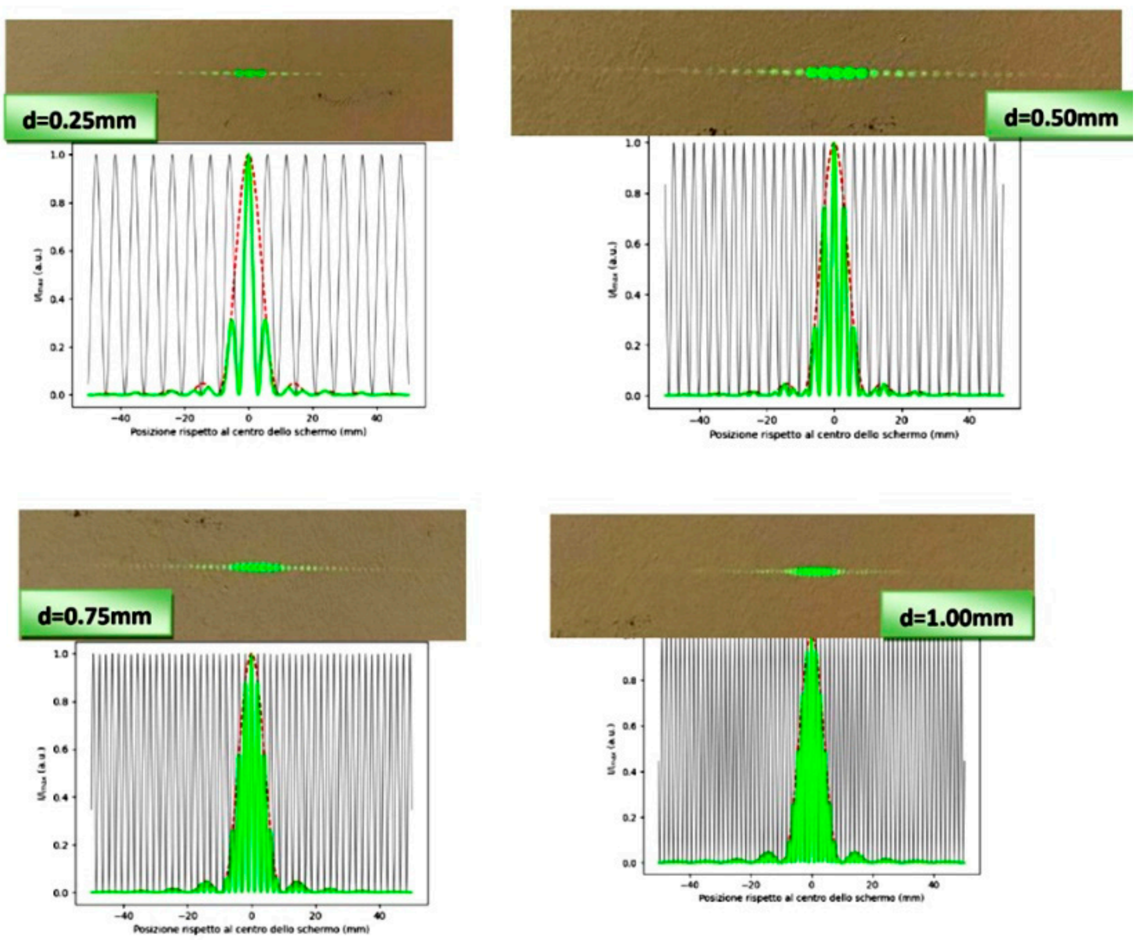

Figure 10. Images taken from the laboratory report written by an undergraduate student [57], where simulations obtained via the Python program are compared with photos of diffraction patterns obtained in the laboratory by using diaphragms with two slits at a variable distance (d).

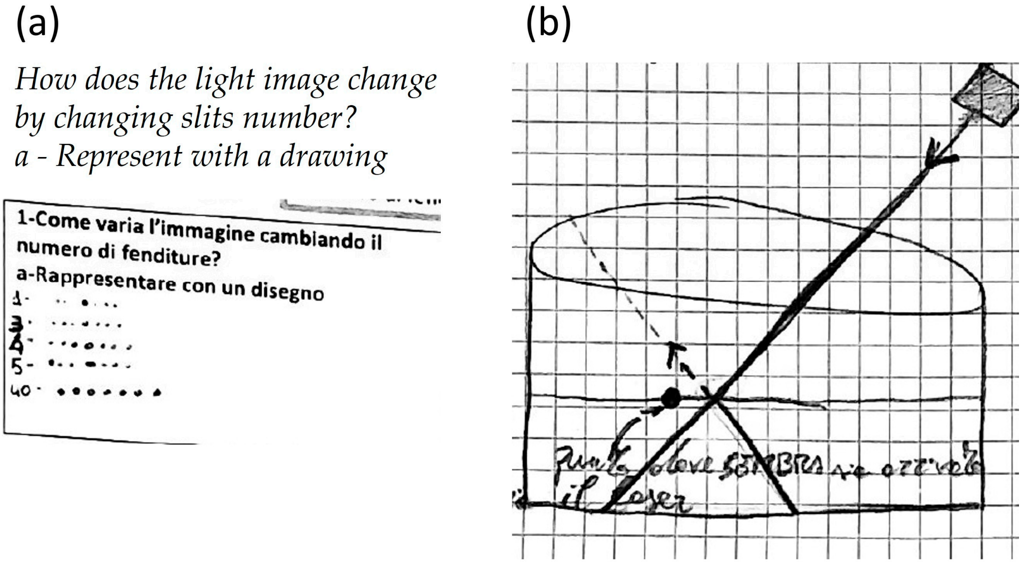

Figure 11. (**a**) A student's answer and drawing (question: "*1-How does the light image change by changing slits number? a-Represent with a drawing*"). The drawing does not show secondary fringes, while the evolution from dashed line to dots is evident. (**b**) A student's drawing representing the experiment of the laser beam crossing the solution–air interface (see also other drawings in the Supplementary Materials).

5. Conclusions

This paper reports the building and the testing of a new didactic sequence concerning the introduction of spectroscopy at the high-school level. The focus of the work was the development of an educational sequence in the framework of the constructivist topic-specific pedagogical content knowledge (TS-PCK) model. The objects of the teaching activities reported in this work are the light phenomena, the basic working principles of a spectroscope, and the introduction of atomic emission and absorption of light. Within this didactic sequence, several teaching strategies were adopted from the STEM and inquiry-based laboratory methods to the historical approach. The whole didactic sequence was developed over the course of two experiments with high-school students from two technical institutes with chemistry curricula (K-11 and K-12 levels). Moreover, several parts of the didactic sequence were also tested with undergraduate students in their first introductory course on spectroscopy. In this paper, we focused our attention on the justification of our conceptual teaching strategy within the TS-PCK model, based on student feedback and careful considerations of learner reasoning and cognitive obstacles.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/educsci13030316/s1, S1: Example of observation form for the "reflection and refraction of light". S2: Example of the reflection form for the "reflection and refraction of light". S3: Example of students' drawings concerning the phenomena of "reflection and refraction of light". S4: Example of students' answers concerning the phenomena of "reflection and refraction of light". S5: Materials given to the students to build their homemade spectroscopes. S6: Evaluation scheme for the activity of the homemade spectroscopes. S7: Plot showing the distribution of the final scores obtained during the first experiment. S8: Plot showing the distribution of the final scores obtained during the second experiment. S9: Plot showing the distribution of the final scores obtained during the third experiment. S10: Questions of the final survey provided to undergraduate students during the third experiment. S11: Results of the final survey provided to undergraduate students during the third experiment.

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