

Training and assessment of experimental competencies from a distance: Optical spectrometry via the Internet

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Summary. — Assessment of experimental competencies is not yet well established. We just began an empirical pilot study, too. This study aims to examine if secondary school students may successfully use a predefined remote lab activity to introduce themselves to atomic physics. The analysis of spectra is a fundamental component for the understanding of wave optics and color perception. Hence, every student should have the opportunity to conduct own optical emission experiments. Since spectrometers are expensive and an accurate calibration is necessary to achieve energy distribution spectra of high quality, we developed a remotely controlled laboratory. We evaluated the experimental set-up and the accompanying worksheet with groups of two to four students in a laboratory condition. Additionally, the emerged learning material was brought to school and tested as a homework activity with 9th-graders replacing the regular introduction to atomic physics. The results show that the experiment presented here can be used by ninth grade students and is useful in connection with the created material for the self-regulated introduction to atomic physics in the context of homework.

1. – Introduction

Since Bohr discovered the relationship between optical spectra and the structure of atoms, spectrometry has been an important method in physics and chemistry. Furthermore, the analysis of spectra is a fundamental component for the understanding of wave optics and color perception. Every student should have the opportunity to conduct his or her own optical emission experiments. Since spectrometers are expensive and an accurate calibration is necessary to achieve energy distribution spectra of high quality, we developed a remotely controlled laboratory.

1.1. *Experimenting in school.* – Experimenting is an essential part of physics and physics education [1-3]. This applies to every kind of demonstration experiments or student activity. Students in German upper secondary education recognize the crucial role

of experiments, even though demonstration experiments dominate and students hands-on activities are rarely carried out [4]. Demonstration experiments are often embedded in a teacher dominated, questioning-developing approach [1,5]. Student experiments are often constrained by precise instructions. However, instructional approaches that link theory and experiments and engage students actively should lead to a deeper understanding [4]. The way of integrating experiments into the lesson plan determines the learning success [2,6]. For the development of the learners performance, not only the experimental time on task is critical, but also the total processing time, including preparation and review [2]. Tesch and Duit assume that the large amount of time needed to carry out student experiments reduces the time for preparation and review in the classroom [2]. They consider this as a possible reason [2], why student experiments do not generally lead to better performances [7].

1.2. *Self-regulated learning.* – The idea of self-regulated learning takes cognitive and emotional perspectives of learning into account [8,9]. One intention amongst others is to foster interest [10,11], self-determination [12], or self-efficacy [13]. Since self-regulation is necessary for effective intentional learning [14], learners should be able to self-regulate their learning process [15]. A suitable approach to foster self-regulated learning in physics education is discovery learning. On the one hand, discovery learning can lead to a deeper understanding. On the other hand, learners may encounter difficulties during discovery learning [16]. In addition, students' ability to engage in self-regulated learning depends on domain specific prior knowledge [17], what in fact stands in contrast to the initial idea of discovery learning. Research on problem-based learning showed that learners with lower prior knowledge use less efficient problem-solving strategies less effective [18]. This finding is transferrable to discovery learning [19-21]. This leads to the question, which domain specific knowledge should be offered to students in a computer-based interactive learning environment inducing discovery learning? Thereby, it must be considered that the knowledge of the meaning of variables per se is not productive, it is very important that students understand how variables are interrelated with each other [22].

1.3. *Experimental competencies.* – Many national science education standards define competencies in science and engineering that all students should be able to demonstrate at subsequent stages in their K-12 learning experience [23].

“Competencies are the cognitive abilities and skills available or learnable for individuals to solve specific problems, as well as the associated motivational, volitional and social willingness and abilities to utilize the problem solutions successfully and responsibly in variable situations” [24].

According to this definition, competencies are domain-specific, learnable, underlying, thus latent variables, which are not directly observable. They are functionally defined and manifest in problem-solving solutions.

1.4. *Assessment of experimental competencies.* – Tools are needed which assess knowledge about scientific theories and findings, and skills of knowledge acquisition as well. Established instruments for assessment of experimental competencies are hands-on experiments (assessment by direct observation and by analyzing students workbooks), computer simulations, and paper-and-pencil tests. According to Shavelson, Ruiz-Promo and Weily, the assessment results from hands-on experiments and computer simulations are directly exchangeable [25]. Since hands-on experiments are not suitable for large-scale assessment, process-oriented experimental competencies may be assessed in virtual labs.

Considering the debate on minimally guided teaching techniques [26-31], assessment tools on experimental competencies including process-oriented inquiry techniques should be familiar to students to prevent cognitive overload while assessing competencies. Furthermore, the format of an assessment tool for a particular learning environment should be similar to the format of the learning environment itself [31]. Therefore, teachers should introduce these assessment tools in class as instructional tools.

1'5. *Experimenting from a distance.* – If expensive, complex, or challenging experimental set-ups are not available or practicable in school, remotely controlled laboratories [32] can offer new, additional possibilities, which enable experimental experience, develop experimental competencies, and furthermore assist discovery learning. For many reasons, experiments should be feasible in distance learning.

Remotely controlled laboratories are a useful supplement to in-class experiments, interactive screen experiments [33], animations and simulations, if

- the experimental set-up is difficult, lengthy or expensive,
- the processing includes dangerous tasks,
- the number of variable parameters is large, so that the experiment could not be implemented as an interactive screen experiment, or
- the processing needs distinct scaffolds, which is of special interest in educational research.

A homework-based activity in a remote lab may deliver a new approach to procedural learning. Furthermore, lab activity as homework could foster problem-based, discovery, and inquiry-based learning and support collaborative and cooperative learning as well.

Remotely controlled laboratories enable students to conduct demonstration experiments in a self-responsible, active and at the same time harmless fashion. In this situation, students can watch their peers during the implementation and learn from their successes and mistakes. Another advantage of remotely controlled laboratories is the ability to record actual data in real time, afflicted by measuring errors. The biggest benefit for the educational research is that fully detailed actions from active users are immediately registered and could be evaluated. All this happens in the absence of repercussion, which means that the user is not disturbed in any way.

1'6. *Four levels of inquiry.* – Banchi and Bell proclaim four levels of inquiry in activities with rising opening and withdrawal of predefined structure: confirmation inquiry, structured inquiry, guided inquiry and open inquiry [34].

- On the first level—*confirmation inquiry*—students confirm a principle through an activity when the results are known in advance.
- On the second level—*structured inquiry*—students investigate a teacher-presented question through a prescribed procedure.
- On the third level—*guided inquiry*—students investigate a teacher-presented question using student designed or student selected procedures.
- On the fourth level—*open inquiry*—students investigate questions that are student formulated through student designed or student selected procedures.

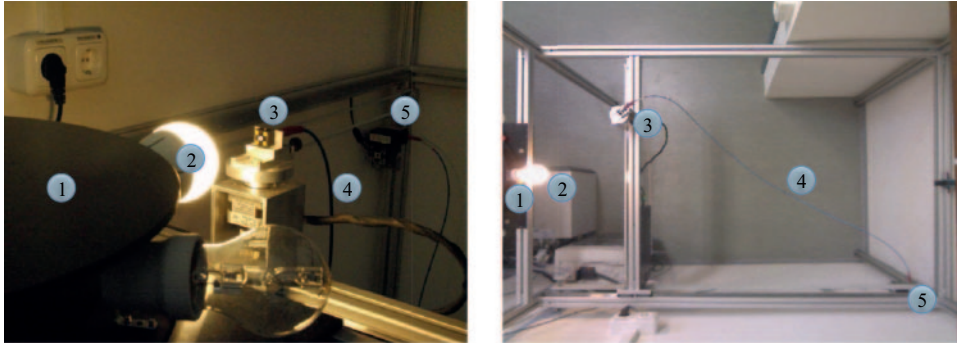


Fig. 1. – Experimental set-up of the spectrometer remote lab implementation (a) in detail and (b) from above: (1) carousel, (2) light source, (3) cosine-corrected probe, (4) optical fiber, (5) spectrometer.

Based on this classification, we developed a remotely controlled laboratory with predefined set-ups selectable according to the class. This reduces the complexity of the lab activity for students. Students can carry out real experiments online. *E.g.*, they can choose from different light bulbs and analyze them with a spectrometer. All user activities are logged by the system without disturbing the students.

2. – Development of a remote-lab experiment on optical spectrometry

For the presented experiment on optical spectrometry via the Internet, three aspects were at the foreground of the technical implementation:

First, the experiment should be usable across many grade levels and in various settings. This affects on the one hand the number of adjustable parameters of the experimental set-up and thus its complexity and on the other hand supports the decision to offer the experiment as isolated gauge and not necessarily to embed it in a learning environment.

Secondly, the operation of the experiment should also be possible via mobile devices such as smartphones and tablets. Furthermore, the measurement values should be displayed in real time also in mobile networks. This had implications for the programming of the operating software and the type of data transmission.

Last, no software installation or setting change should be necessary and a data transmission ensured even with restrictive firewalls. In addition, due to the use of a WebSocket service the experiment does not require its own static IP address.

2.1. *Experimental set-up.* – The developed experiment on optical spectrometry allows the assessment of customary lamps with E 27 lamp sockets (fig. 1). For that purpose, the irradiation at a certain position is collected with an optical fiber and analyzed with a USB compact spectrometer. The spectrometer used projects the received light through a $25\ \mu\text{m}$ entrance slit onto a linear silicon CCD array with 651 active pixels offering approximately 2.0 nm optical resolution full width at half maximum. Radiation within a wavelength range of 350–1000 nm is recorded with 12-bit A/D resolution. With this, intensities are measured within a range of 0–4096 arbitrary units.

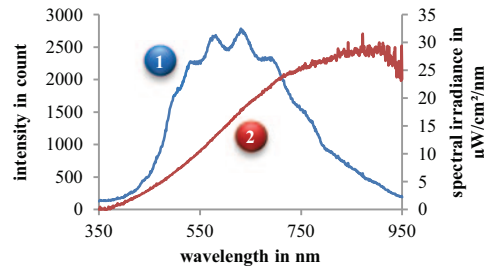


Fig. 2. – (1) Measured spectrum of a tungsten halogen lamp and (2) spectral irradiance.

2.2. The detectors field of view. – Some experimental objectives take into account the radiant characteristics of different light sources. In order to analyze the radiation field around a particular light source under constant experimental conditions, the spectral irradiance on a probe is measured.

The irradiance is the total power of electromagnetic radiation per unit area incident on a surface, such as the fiber’s cross-section at its tip. Nevertheless, with a bare fiber it is not possible to measure the true irradiance because the coupling of light into the fiber is highly dependent on the angle of incidence. Instead, the irradiance should be proportional to the cosine of the angle of incidence [35]. Furthermore, a probe with a 180-degree field of view is needed. The spectrometers manufacturer provides a so-called cosine corrector: a window made from opaline glass mountable on the tip of the optical fiber creating a dependency on the angle of incidence that is nearly proportional to the cosine [36].

2.3. Spectral sensitivity and calibration of a radiometric detector. – Unfortunately, the following aspect often is not sufficiently discussed. “Knowledge of the spectral irradiance responsivity of a meter is critical for high accuracy measurements of sources with different spectral power distributions” [37].

Figure 2 shows the measured spectrum of a customary tungsten halogen lamp (1). For learning purposes, this graph requires special considerations. Students may interpret this spectrum as blackbody radiation, on the one hand due to the form of the curve, and on the other hand based on their knowledge that thermic radiators like tungsten lamps may be regarded as blackbody radiators. Actually, a tungsten lamp radiates only a small part (about 4%) of its radiation in the visual part of the electromagnetic spectrum. The important point to keep in mind is that the spectral sensitivity of the

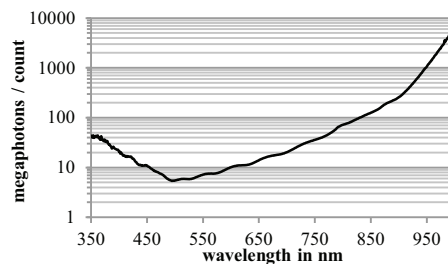


Fig. 3. – Spectral sensitivity of the detector system used for the experimental set-up.

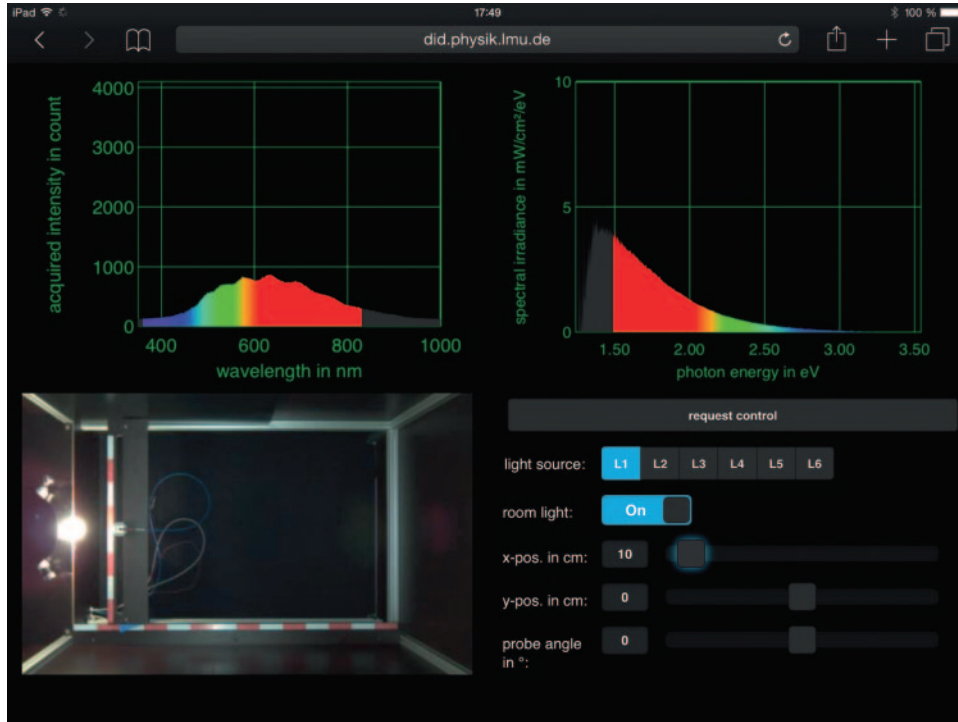


Fig. 4. – One exemplary implementation of the adjustable graphical user interface.

detector system is extremely dependent on the irradiated wavelength. Figure 3 shows the measured spectral sensitivity of the detector system used for the experimental set-up with a logarithmic scaling. Attention should be paid to the fact that there is a factor of 1000 in the spectral sensitivity between 500 nm and 1000 nm. Without accurate calibration, neither two measured intensities at different wavelengths may be compared nor can any statements be made about the spectral power distribution of the radiation examined. For the calibration of the radiometric system used, the German distributor of the spectrometers manufacturer kindly provided us with a NIST traceable radiometric calibration standard. In this case, it is a calibrated tungsten halogen light source with a well-known spectral power distribution. This calibration standard provides absolute spectral irradiance in $\mu\text{W}/\text{cm}/\text{nm}$ at the fiber port. The spectrometer can be calibrated specifically for a bare fiber or a fiber with attached cosine corrector.

2.4. Experimental processing. – Several parameters of the experimental set-up may be changed by the user (fig. 4). For example, the acquisition parameters for the spectrometer may be set, like the integration time, the boxcar width (averaging over neighboring pixels), or the samples to average (averaging over two or more subsequent spectra). Furthermore, users can choose from six standard light bulbs mounted on a carousel like tungsten incandescent light bulbs, halogen incandescent lamps, cool white and soft white compact fluorescent lamps, light-emitting diode lamps or special bulbs (see fig. 1). The cosine-corrected probe may be moved and positioned in front of the bulb in a field of 115×65 square centimeters. The probe may be rotated too. These many differ-

ent parameters provide many opportunities and guarantee an authentic experimental experience.

2.5. *Experimental aims and objectives.* – With the experimental set-up described above, many different objectives can be followed by students. They may compare spectra from different lamps and thus rate the usability of the light sources for a certain purpose. Students may assess color temperature and color fault. They may compare the radiated light with the color sensitivity of the human eye. Students may distinguish between physical and physiological quantities. They can analyze the energy efficiency of customary lamps.

The free positioning of the probe allows further experiments like analyzing the decrease of the spectral irradiance in proportion to the square of the distance from the source or the spatial spectral radiant emittance. With compact fluorescent lamps, differences can be noticed between the light coming from the gas discharge and the light coming from the fluorescent layer. Expert learners may examine, distinguish, classify, and rate the directional characteristics of radiation from different light sources. This is very interesting with light emitting diodes, which often radiate highly anisotropic.

3. – Pilot study

The learning material for the introduction to atomic physics was created as an initial pilot study with ninth-grade students in a secondary school in Germany. While continuous and monochromatic spectra should already be familiar from prior teaching discrete spectra is a new concept. The appearing emission lines are identified with electron transitions in the electron shell and thus introduce the topic of atomic physics. The course material is designed for self-regulated study within the context of homework. The following tasks should be tackled during the study of the work material: Students are expected to

- describe spectra of various light sources,
- name categories of spectra,
- investigate different light sources and assign them to these categories,
- measure the spectral irradiance during exposure to a compact fluorescent lamp,
- carry out quantitative comparisons of two spectral lines, as well as
- perform energy conversions.

3.1. *Research instruments.* – The work material itself initially is the instrument and object of this first exploratory study. The difficulty of the individual subtasks is of particular interest here. In addition, the actions of the students were recorded during the experiment.

3.2. *Sample.* – A pilot study on the work material was conducted with four classes in secondary schools in Germany. Three classes from grades eight, ten, and eleven worked on the material under laboratory conditions, for a limited time, and in groups of two to four students. A ninth grade class was introduced to the material in school according to the intended purpose and had to work on it within a week as part of their homework.

3.3. Evaluation. – In addition to the content evaluation of the solutions, the answers to problems with an open response format were subjected to a qualitative content analysis according to Mayring [38]. The frequencies of certain inductively determined response categories were analyzed. For simple allocation tasks, the response frequencies were measured.

4. – Results

This first exploratory study aims at reviewing the suitability of the developed experimental set-up, as well as reviewing the created course material for a self-regulated introduction to atomic physics in the context of homework at ninth grade level.

4.1. Verbal description of figurative displayed spectra. – When verbally describing figurative and colorful represented spectra (monochromatic, continuous, discrete), students often named the spectrum shown or described the trend from left to right, from red to violet. Often, the spectrum was described as a curve together with its trend (such as “hyperbolic”, “exponentially falling”). In addition, the intensities of different colors were compared. Occasionally, the width of the spectral range covered was described. A reference to the light source used was rarely made.

4.2. Naming categories of spectra. – To build on previous lessons and reactivate prior knowledge, the students were asked to name the represented spectra. If no technical term was known, they were expected to give a short descriptive name. The technical terms were recalled only sporadically. Often, no information was remembered. Sometimes, other types of names were given. In this case, the students used associations with landscapes (for example “alpine spectrum”, “stalagmite”) or buildings (such as “half-pipe”, “spire”) or the spectrum was described as a curve (such as “hyperbolic spectrum”). Rarely, other associations were made (such as “lie detector”, “ECG”).

4.3. Assigning light from various lamps to categories of spectra. – Tasked with assigning the investigated light sources to the above named categories of spectra, within the experiment, 65% of the students carried out all assignments as expected. A LED color changer and a white LED lamp represented particular difficulties for the students, as was to be expected. The responses to the secondary question, “Which light sources were difficult to assign? Describe in as much detail as possible, what you found difficult”. show that the students hesitated between identifying them as monochromatic or continuous when asked to assign the spectra of the LED lamps.

4.4. Quantitative comparison of two emission lines and energy conversions. – The quantitative comparison of two emission lines and the required energy conversions proved so difficult for many students of all grade levels that only few completely worked out this part of the problem.

The last task was “Compare the two emission lines in relation to the number of measured photons, the photon energy and the corresponding total energy”. A case study from the ninth grade provided the following response: “Violet has higher photon energy than red-orange. However, the total energy is higher in red-orange because twice as many red-orange photons are emitted by the lamp. Nevertheless, the total energy is not much higher than in violet, because violet has higher photon energy”.

5. – Discussion

The experiment on optical spectrometry via the Internet presented here can be used by ninth grade students and is useful in connection with the created material for the self-regulated introduction to atomic physics in the context of homework. Even if not all the tasks were fully completed by all the students, the described case study shows that the importance of the distinction between photon energy and radiant energy can be independently processed at ninth grade level.

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