Seeing the Light: The SpecUP Educational Spectrophotometer

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ABSTRACT

Spectrophotometry is a cross-cutting analytical technique, which finds use in disciplines ranging from chemistry to pharmacy, biochemistry, food science and physics. The SpecUP (Spectrophotometer of the University of Pretoria) is an educational spectrophotometer which was developed so that students could build their own instruments from components in a kit, and then utilise it to generate analytically useful results. This initiative allows for institutions to have more spectroscopy equipment available, as the SpecUP costs less than $40 as opposed to ~$2 000 which is the cost of an entry-level commercial instrument. This is of particular importance in a developing country context, where student numbers are typically high and resources are scarce. In addition, the SpecUP has moving parts and an open design which allows users to understand what is inside the "black box" of commercial instruments and to discover what happens when they adjust components, allowing for active, inquiry-based learning. The SpecUP user network currently spans South Africa, Tunisia, Namibia, Lesotho, Botswana, Kenya, Swaziland, Zimbabwe, Zambia, Ivory Coast, Egypt, Turkey and Italy.

Keywords: SpecUP, spectrophotometry, active learning, inquiry-based learning, educational spectrophotometer, optics

1. INTRODUCTION

The field of science is a challenging one, which requires teachers to convey complex fundamental concepts to students before building on these in terms of depth of content as well as breadth (such as in applications of scientific principles). It is therefore of paramount importance that teachers present these fundamental concepts in a suitable manner which allows students to engage with the material and to develop a solid academic foundation. It is critical for students to have opportunities to develop their understanding of concepts and to construct knowledge through hands-on learning. Indeed, the central and essential role of laboratory practicals in science education has been widely reported[1-3].

Modern commercial scientific instrumentation used to analyse samples is built so as to be rugged and to provide reproducible and accurate analytical results. As a consequence, user interaction with the actual instrument components is usually very limited and operation is rather based on interaction with a computer interface. This has the concomitant disadvantage in the training of students, as opportunities for hands-on learning are very limited and therefore a student's understanding of what goes on in the "black box" of instruments may be very poor or even incorrect. This is a concern, as students then cannot adequately reflect on the meaning of the results; whether they make scientific sense or whether trouble shooting is needed (and indeed where to start with this).

This situation is particularly true for spectrophotometers where typically the only direct interaction the student has with the instrument itself is the insertion of their sample, and after pressing a button a number appears on the screen, which is the analytical result. Spectroscopy is an important optical analytical technique, which is a component of numerous tertiary science courses ranging from chemistry to physics and food science, as it provides information on the composition of samples as well as the concentration of the chemical compounds in the sample solutions. Spectroscopy is therefore widely used in a diversity of industries: such as in the pharmaceutical industry to determine the absence of impurities in medicinal preparations or the concentration of the active ingredient; in the food industry to determine the composition of food and beverages, such as the ethanol content of wine or the aspartame content of an artificial sweetener; and in the environmental sciences field to determine the concentration of metal pollutants in river water, to name but a few.

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In undergraduate chemistry in South Africa, the principles of spectrophotometry are part of the third year analytical chemistry curriculum, where the theory is complemented by an integral practical component. Chemistry modules have historically poor pass rates and many are regarded as "high impact modules" as a consequence, due to the fact that poor performance in these courses leads to an extended time for students to complete their degrees. In response to these teaching challenges, I decided it would be beneficial to the students' understanding if I unpacked the abstract ("black box") concepts with respect to analytical chemistry, and specifically for spectrophotometry, in a hands-on manner which allows for inquiry-based learning. A unique "build-it-yourself" educational spectrophotometer was thus designed, which students could assemble from a kit of components and then use to analyse samples and generate analytically useful results. In this way, students would know what components are required to perform a spectrophotometric analysis (i.e. what is inside the "black box") and also how each of these components affect the results obtained.

2. METHODOLOGY

2.1 Development of the SpecUP

The educational spectrophotometer, called the SpecUP (Spectrophotometer of the University of Pretoria), was developed in 2013 and then subsequently implemented in the third year undergraduate analytical chemistry module at the University of Pretoria (UP) from 2014.

In order to develop a suitable instrument, examples of possible "DIY" spectrophotometers were obtained from the literature as a starting point and these were merged, modified and improved in order to meet our requirements. The SpecUP which was thus developed has a unique design with moveable components, which is made possible due to the use of a domestic telescopic drawer runner/slide as the base of the instrument. Light emitting diodes (LEDs) of various colours, or alternatively a white LED with a diffraction grating, are used as the light source and a light dependent resistor (LDR) serves as the detector. It is battery powered, therefore no electricity is required, and the components are cheap and are readily available from general electronics stores and building suppliers. Further instrumental design details can be found in the journal article which was published on the SpecUP[4].

2.2 Assessment of the impact of the SpecUP

The SpecUP was included in an Analytical Chemistry III practical in 2014 to enhance student learning outcomes. In this practical, students compare the results they obtain with the educational instrument to a commercial one, as it is an important skill for these students to be able to understand the strengths and limitations of different analytical measurement techniques. Assessment of these practicals is via the submission of practical reports, which the students write after completing the practical.

Students also complete questionnaires during the practical session before and after using the SpecUP, respectively, in order to allow for the impact of this teaching innovation to be assessed, both in terms of the students' fundamental understanding of spectrophotometry and spectrophotometers, as well as their perceptions in this regard.

3. RESULTS AND DISCUSSION

Pressures in terms of increasing student numbers for the third year analytical chemistry course at UP (from 27 students in 2010 to 60 in 2015) and limited financial resources, which had prevented the purchase of additional commercial spectrophotometers, had meant that students were working in large groups in the practical sessions and were getting very limited hands on experience. The SpecUP addressed these issues, in that it is a cost effective alternative to commercial systems, yet it can generate analytically useful results. The SpecUP costs less than $40 as opposed to ~$2 000 for an entry level commercial instrument, therefore more SpecUP instruments can be acquired and student engagement and learning can be enhanced.

In terms of results, in 2014 after implementation of the SpecUP, the average mark for the Analytical Chemistry III spectrophotometry practical at UP was 83%, whilst the overall average for all practicals was 67%. In 2015, the average was 88% for the spectrophotometry practical and the overall average was 76%. It is evident that the constructive alignment that the SpecUP provides has assisted in improving learning[5] and in developing scientists who are more proficient in the laboratory, which is critical in serving the needs and requirements of both the industrial and academic employers of our graduates.

From the first set of questionnaire responses which have been processed (which also include some non-UP students, as discussed in Section 4 on Outreach), it was evident that although most of the students had learnt about the theory, a third had no practical experience of spectrophotometry (Fig. 1) and many were uncertain or had incorrect perceptions of spectrophotometry before completing the practical (evident from the spread in student's responses in Fig. 2). Students have responded very positively regarding use of the SpecUP, as can be seen from the results presented in Fig. 3.

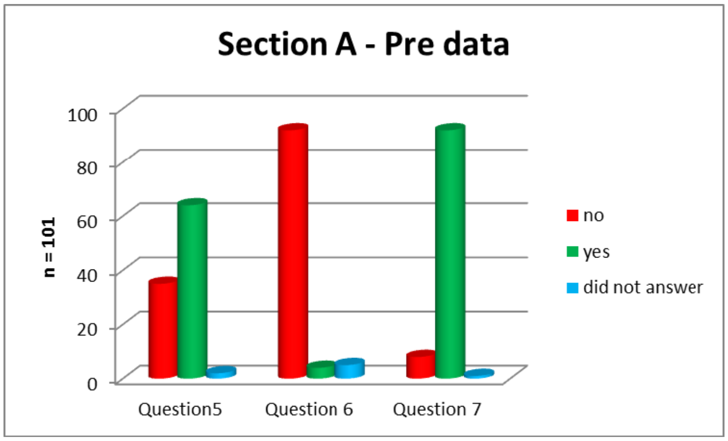

Figure 1. Response of students to questions prior to using the SpecUP. Question 5: Have you ever used a commercial spectrophotometer? Question 6: Have you ever used the SpecUP spectrophotometer? Question 7: Have you been taught the theoretical aspects of spectrophotometry in lectures?

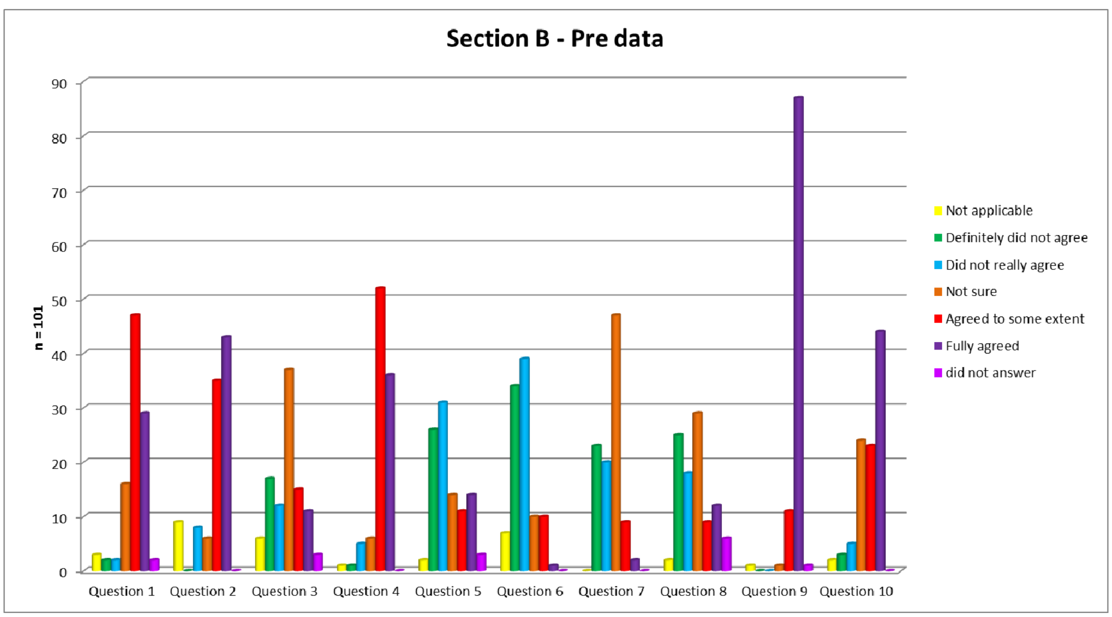

Figure 2. Response of students to theoretical questions prior to using the SpecUP. Question 3: Spectrophotometers do not have moving components. Question 5: The only thing that is needed to be done to obtain a result from a spectrophotometer is to place the sample cuvette inside the instrument. Question 9: I would recommend that all chemistry students get hands-on experience with spectrophotometers.

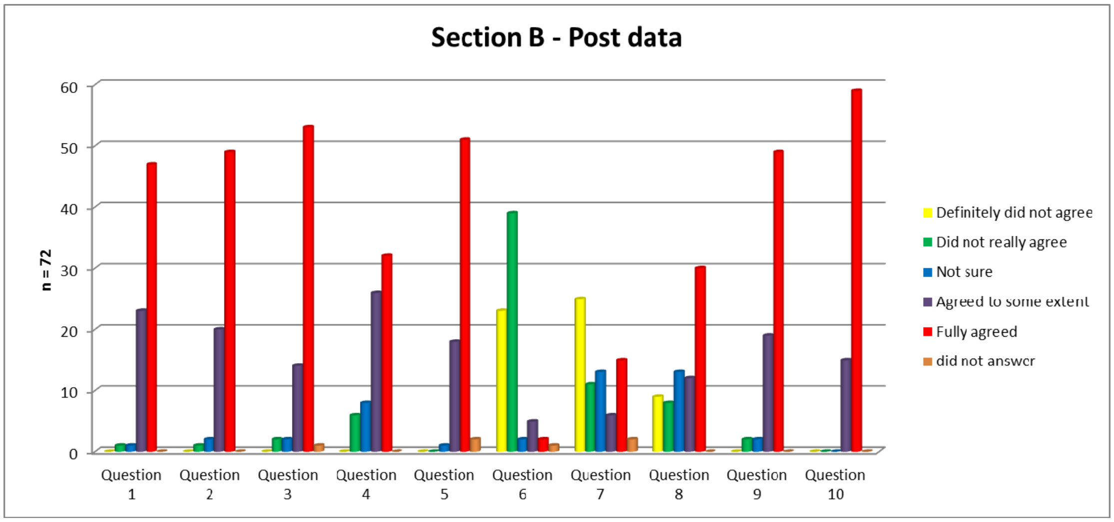

Figure 3. Response of students to questions after using the SpecUP. Question 2: The SpecUP helped me to understand spectrophotometry. Question 3: I enjoyed moving the components of the SpecUP to see the effect it had on the results. Question 5: The SpecUP made me think about how a spectrophotometer works.

4. OUTREACH INITIATIVES

After the successful development of the SpecUP, funding for the project was successfully sourced (from the African Laser Centre, Tunisian Optics Society, South African Department of Science and Technology, and the Royal Society of Chemistry) and SpecUP kits were prepared and distributed to a number of institutions throughout Africa via training workshops. To date three workshops have been held in South Africa and two in Tunisia. Academic attendees of these workshops were provided with SpecUP kits free-of-charge to implement at their institutions. They were also provided with educational resources including the questionnaires to be completed by students before and after usage of the SpecUP, in order to gain an objective evaluation of the impact of the kit on their students' understanding and perceptions of spectrophotometry. These are then sent to me, where the information is entered into a database for overall assessment of the impact of the SpecUP in student learning. Numerous invited conference presentations have also been given on the SpecUP project, including at four International Year of Light (IYL) events in 2015, which have generated significant interest in this educational optics instrument.

The SpecUP has been very well received, and the approach employed of training the trainers has had a multiplier effect in the roll out and implementation of this educational instrument. The SpecUP user network currently spans South Africa (seven universities), Tunisia, Namibia, Lesotho, Botswana, Kenya, Swaziland, Zimbabwe, Zambia, Ivory Coast, Egypt, Turkey and Italy. This novel teaching intervention has thereby had an impact in numerous developing countries in Africa where student numbers are large but financial resources are often severely limited.

5. CONCLUDING COMMENTS

It is vital to provide opportunities for students to really engage with optics concepts and instrumentation at a fundamental level via active learning if we are to educate and develop the next generation of innovators and entrepreneurs in this field. Ultimately, promotion of discovery, creativity and innovation is fundamental to developing and nurturing the next generation of scientists who can excel in a knowledge-based economy, and the SpecUP teaching intervention provides positive contributions in these aspects.

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