HANDS-ON SPECTROSCOPY: INSIDE AND OUTSIDE THE FIRST-YEAR LABORATORY

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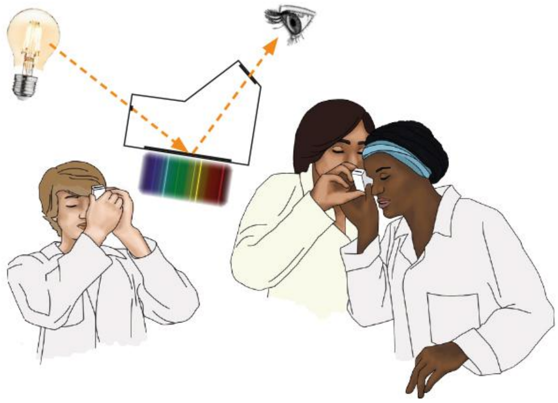
ABSTRACT

This article reports on the introduction of a simple, portable, low-cost and hands-on spectral tool for first-year chemistry students to use inside the laboratory and its spontaneous dissemination outside of the laboratory. The Mini Spec is a refinement of the Schwabacher mini spectroscope in terms of simplicity and language load on the students. Inside the laboratory, students were supported with construction references resulting in reduced construction time and improved student engagement and performance. Two months after the laboratory session, a voluntary Qualtrics survey was used to explore spontaneous outreach. The dissemination of the Mini Spec was mapped across South Africa, the variety of languages used were documented and data on the value of spontaneous outreach for the students and for their audience was gathered. Evidence of student enjoyment, student learning and of students developing into scientists was collected along with audience enjoyment, audience learning and interest in science.

GRAPHICAL ABSTRACT



KEYWORDS
First-Year Undergraduate/General; Laboratory Instruction; Public Understanding/Outreach; Hands-On Learning/Manipulatives; Spectroscopy.

INTRODUCTION

Spectroscopy in general, and emission lines in particular, are areas where novice students struggle due to the abstract nature of the content and the ease with which misconceptions arise or persist.[1,2,3] Traditional analytical spectral instruments and experiments are often complex and costly. Furthermore, the students' use of commercial equipment is frequently results-based, with students being more concerned about getting the correct answer than understanding the components of the equipment, or the concepts behind the laboratory exercise.[4] This Journal, among others, has published a number of articles that recommend spectroscopy experiments with hands-on, non-commercial spectral tools to enhance student learning.[5-12] This article intends to add to this discussion by reporting on the refinement, evaluation and subsequent outreach of an educational spectral tool used by first-year general chemistry students on an academic development program in South Africa.

General chemistry is a core curriculum component for first-year students enrolled in science academic development programs. The laboratory component of this course was purposefully designed to complement the taught component through providing an opportunity to further develop meaningful learning around a certain topic. Prior to the introduction of this spectral laboratory experiment, there was no practical or laboratory component to support the teaching of atomic structure and emission spectra in general chemistry in the academic development program offered at the University of Pretoria. Academic development programs (in the form of extended, foundational or augmented programs) have become prevalent in South Africa to facilitate access to tertiary education by offering holistic academic and psychosocial support to students.[13] The offering of this particular academic development program is not limited to student learning but also extends in the form of services and outreach to the community it is situated within.

The purpose of this study was to provide academically underprepared students with a hands-on experience of spectroscopy, thereby making an abstract topic accessible so that learning can happen. We were cognisant of the cognitive demands of the exercise and sought to maximise engagement and learning. In order to evaluate the success of the experiment we collected data on performance (primary evidence) and informal spontaneous outreach (secondary evidence). We selected the mini spectroscope developed by Schwabacher[9] as the chosen spectral tool for the laboratory session on this course, based on the following considerations:

- Cost, as funding was limited
- Portability of the spectral tool with a low risk of damage
- Simplicity of the design, in terms of lowered cognitive demands of construction and use
- The potential to be used for spontaneous outreach

The last two considerations are of particular importance on a national level to facilitate inclusive quality education.[14] Two of the facets of inclusive education include acknowledging and supporting differences in language proficiency and broadening of learning into the home and communities,[14] which may be addressed through outreach. Outreach is generally organized by institutions or centers that provide guidelines and support to their members who carry out outreach programs in either formal or informal settings.[15] Everyday science learning is on the other extreme of the continuum of learning environments in that it is driven by the personal interests of the public and usually occurs in everyday settings.[16] As such, it is unstructured, unobtrusive in nature and able to engage an audience beyond the scope of most of the other types of outreach. For the purposes of this article, spontaneous outreach is defined as a subset of everyday science learning in which the student functions autonomously, according to their own interests, and interacts spontaneously with their chosen audience on mutually negotiated terms. The students share their learning experiences spontaneously outside of the classroom without being prompted or encouraged to do so, thereby revealing positive affective outcomes of the learning experience, such as enjoyment, confidence and agency.

Refinement of the Mini Spec

The majority of the students on this program are academically underprepared and have limited laboratory experience from high school, if any experience at all. The medium of instruction across the University is English, however, more than 80% of the students enrolled in this program use English as an additional language. In light of these variables, Cognitive Load Theory[17,18] was used to inform the refinement of the original Schwabacher mini spectroscope,[9] which was renamed as the Mini Spec (see Figure 1).

The first level of refinement focused on reducing extraneous cognitive load through simplifications to the original template and the instructions for its assembly. The template was refined by removing wording, printing a uniformly black interior to limit excess light refraction and printing directly onto cardboard to strengthen the structure. The instructions were rewritten by removing excess wording, making the instructions more direct and re-formatting the layout. The instructions were part of the laboratory manual given to students (see supplemental information). The manual also included a short introduction which was designed to activate students' prior knowledge by bringing together the macroscopic, microscopic and theoretical components of emission spectroscopy.

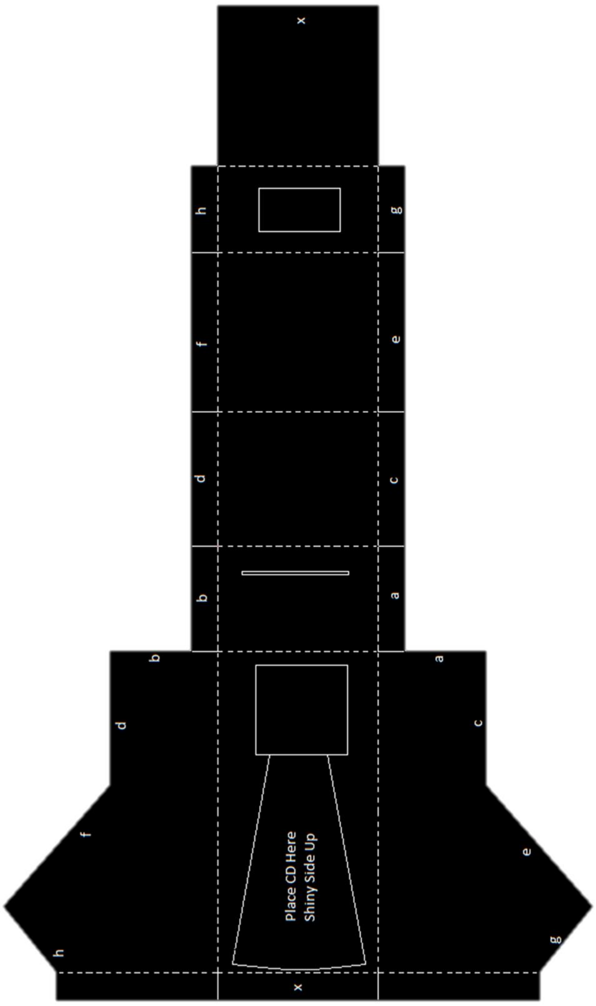


Figure 1. Refined Mini Spec template.

It has been reported that learning in a second language medium may use up to 20% of students' available working memory's processing power in language related tasks, limiting their capacity for problem solving and reasoning.[19] In light of this, the design of the laboratory experiment was sensitive to additional demands placed on students working memory[20] by language and translation. Therefore, in a second level of refinement, students were supplied with construction references i.e. a half completed Mini Spec and a fully completed Mini Spec (see Figure 2) in addition to the standard construction instructions. A reduction in cognitive load and improved processing was expected to manifest as a reduction in construction time, and, result in improved student performance.

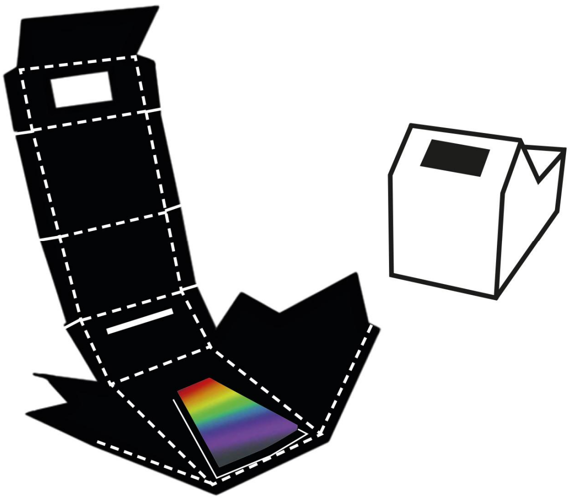


Figure 2. Diagram of the construction references provided in level 2 of refinement.

EXPLANATION OF THE EXPERIMENT

Each student was provided with a refined Mini Spec template and 1/16th of a CD. Students were expected to bring along their own scissors and a stick of glue; clear tape was also provided to strengthen the final structure of the Mini Spec. Students were expected to individually construct a Mini Spec, understand its components and use it to observe diffraction from four different light sources: overhead fluorescent lights, energy saver globes, incandescent globes and natural sunlight (see Figure 3). In addition to making observations students were expected to draw conclusions from their observations in terms of the nature of light from different sources.

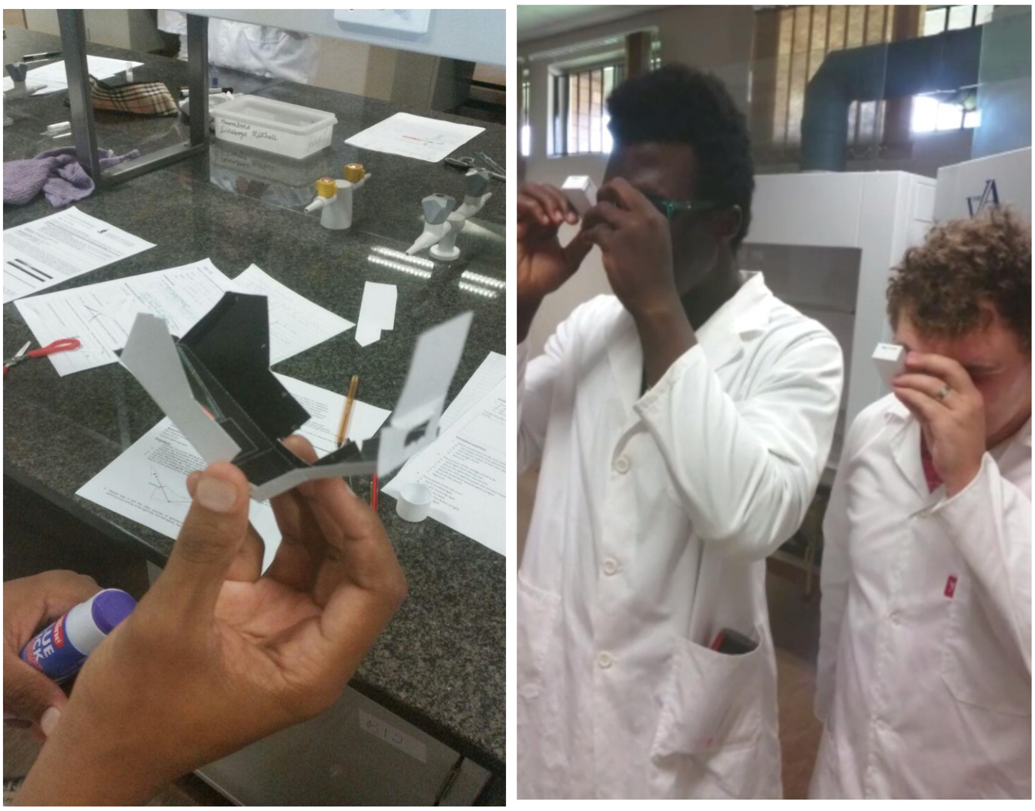


Figure 3. Student constructing a Mini Spec (left). Students using their Mini Specs to observe overhead fluorescent light (right).

Students recorded their observations and conclusions on a report sheet which takes the place of an experimental write up for students on this program. The report sheet contained guided questions to build and interrogate students' understanding of the components of the Mini Spec; specifically the slit and wedge of CD which represent two key components of a spectroscope: the focusing lens and diffraction grating. The decision to implement guided questions in the report sheet was due to a small scale investigation that revealed that quality of the students' answers was linked to the scaffolding given the report sheet items (See Table 1).

Table 1. Student answers improved by guided questions.

Component	*Question in report sheet*	*Representative student response*
Slit	*Original:* What is the purpose of the slit?	“Make a narrow beam”
	Guided: What is the purpose of the slit in your Mini Spec? What would happen if the slit was too large? Or too small?	“The slit minimizes incoming light and focuses a beam of light directly onto the piece of CD”
Wedge of CD	*Original:* What is the purpose of the piece of CD in your Mini Spec?	“It shows the spectrum of lights for different types of lights”
	Guided: How is the piece of CD in your mini spec similar to a prism?	“It refracts the light in the same way that a prism does by separating the light into its different colors”

The main focus of the report sheet was observational data capture, students making distinctions in terms of spectral type and being able to evaluate the significance of their findings. Box 1 Provides sample data from the report sheet.

Box 1. Excerpt from a report sheet submitted by Nala (pseudonym)

Complete the following table by marking the correct colours using an (X)

	Colour observed							Type of spectrum	
Light source	Red	Orange	Yellow	Green	Blue	Indigo	Violet	Discrete	Continuous
Overhead fluorescent light	*x*	*x*		*x*		*x*	*x*	*x*	
Energy saver light	*x*	*x*		*x*	*x*	*x*		*x*	
Incandescent light	*x*	*x*	*x*	*x*	*x*				*x*
Natural sunlight	*x*	*x*	*x*	*x*	*x*	*x*	*x*		*x*

Compare natural light to the artificial light sources in terms of the colours observed with your Mini Spec and the Type of spectrum observed. Fully explain these findings.

Natural light is a true continuous spectrum as I can see all of the colours of the rainbow blurred into one. The incandescent globe emits light that is similar to natural light, but not all of the colours are seen. The other artificial light sources give bands of colour with dark patches in between, these are discrete spectra. Each light source has its own unique spectrum.

Students were at liberty to interact with their peers, laboratory demonstrators and the lecturer on duty throughout the laboratory session. The correct functioning of each Mini Spec was assessed by a lab demonstrator before students began observations of the four types of light sources. Students were also assisted with angling their Mini Specs to best capture the light from the source.

Over a semester, students complete six laboratory sessions; the Mini Spec experiment was scheduled during one of the regular three hour sessions. However, students at this level should be able to complete construction, observations and write up within two hours if required.

RESULTS AND DISCUSSION

This section is divided into two subsections, the first subsection "Year 1: In the lab" describes how the Mini Spec experiment went in the laboratory setting. The laboratory findings discussed are based on observations carried out by the lecturer on duty, the construction time required by students and their performance in specific report sheet questions (see Box 1).

In the second run of the experiment, in the following year, all students received simplified templates and had access to construction references. The laboratory was not the focus of our study in year 2, but the focus was to gauge the extent and value of unsolicited penetration of the Mini Spec into the students' homes and communities using a Qualtrix survey. This is described in the second sub-section, "Year 2: Spontaneous Outreach".

Year 1: In the lab

Students were randomly divided into two groups in year 1. The control group experienced level one refinements only whereas the experimental group experienced both level 1 and 2 refinements i.e. students received both the simplified templates and had access to construction references of templates that were half and fully built.

Lecturers observed that most students managed to construct the Mini Spec independently regardless of whether construction references were available, or not. Overall, students were enthusiastic, engaged and coped well in making observations with their Mini Specs. The construction time required by students in the control group ($M = 23.2$ min, $SD = 7.7$ min, $n = 214$) was greater than the construction time for the experimental group ($M = 21.2$ min, $SD = 6.9$ min, $n = 194$), see Figure 4. The findings of the t-test confirmed that the difference in the construction time taken between the control and experimental group was significant, $t(406) = 2.76$, $p = 0.003$, Cohen $d = 0.4$.

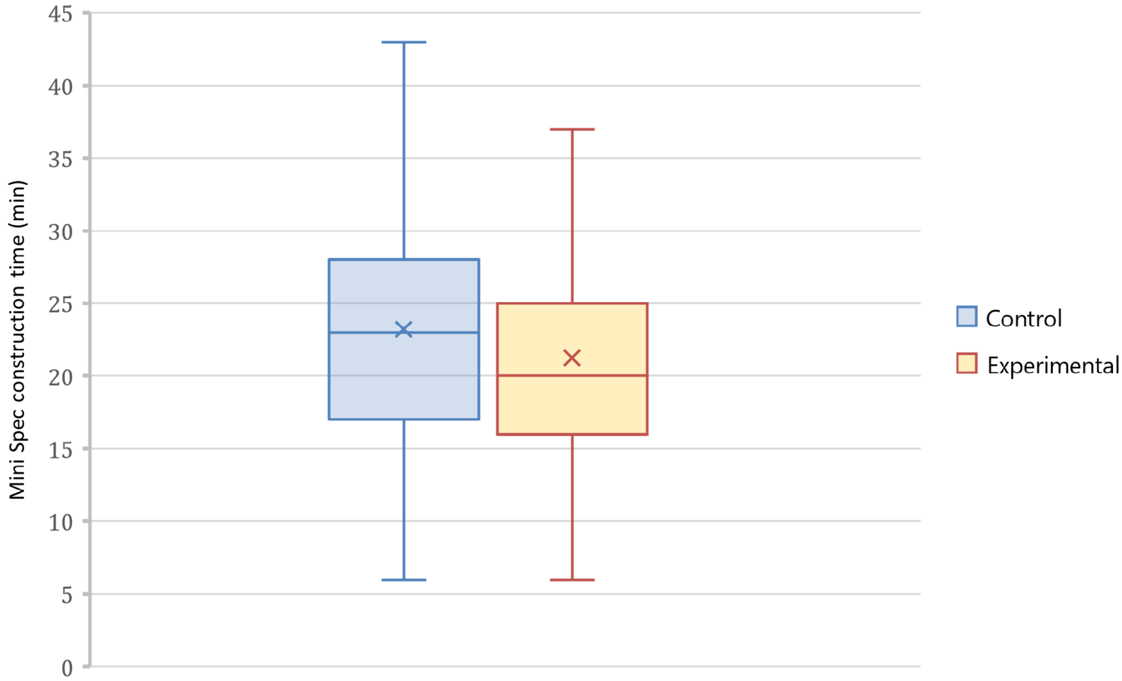


Figure 4. Box and whisker plot of construction time per group

Lecturers noted that the reduction in time on building for the experimental group did not translate into less time spent in the laboratory, in fact it allowed for slightly more time working with the Mini Spec and discussion of observations with peers, lab demonstrators and lecturers. This observation was further supported by student performance on specific report sheet items (see Box 1 and Figure 5). The performance of the control (M = 68.9%, SD = 12.2%, n = 214) was lower than the experimental group (M = 73.2 %, SD = 10.1 %, n = 198). The findings of the t-test showed that the difference in performance between the control and experimental group was in fact significant, t (405) = 3.98, p = 0.0005, Cohen d = 0.4.

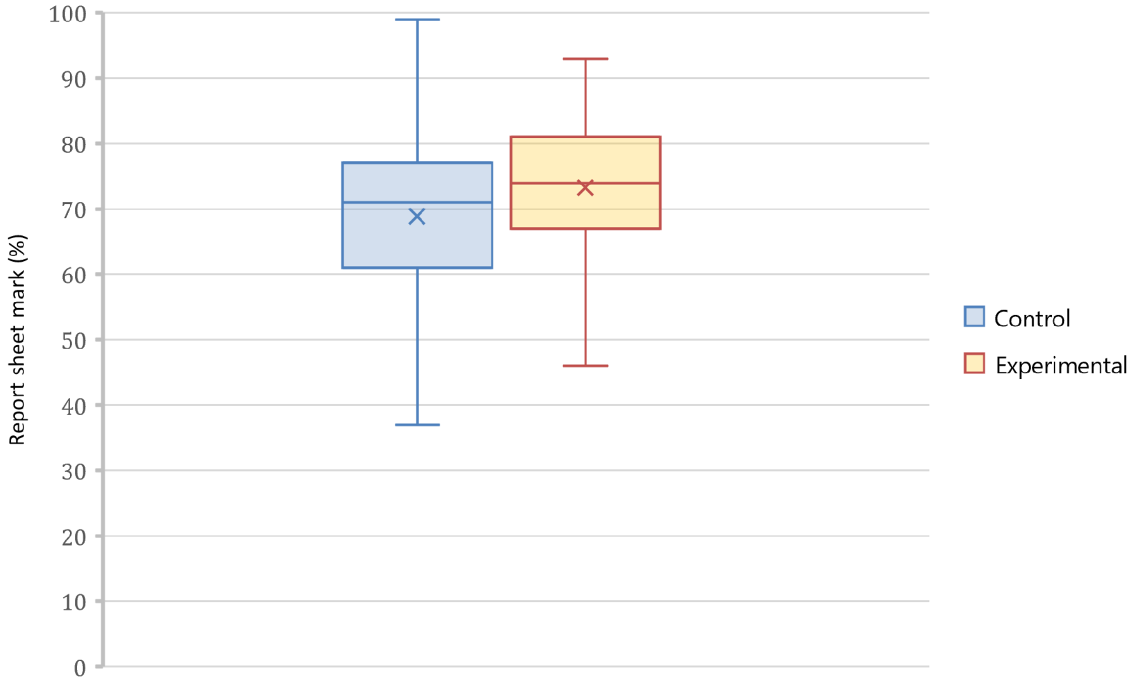


Figure 5. Box and whisker plot of student performance in the report sheet per group

These laboratory findings are in line with the large-scale review by Augustian and Seery, who established that by supporting cognitive load experienced by students through pre-laboratory exercises, student leaning could be managed in complex environments.[21] Furthermore, pre-laboratory exercises which manage cognitive load have also been shown to increase student confidence.[22] The voluntary dissemination of the Mini Spec discussed in the next section provides confirmation of the confidence and motivation generated inside the laboratory. This spontaneous outreach is especially pertinent as students on academic development programs often lack confidence in their own abilities.[23]

Year 2: Spontaneous outreach outside of the lab

The first-year students did not receive any instruction or suggestion about sharing their Mini Spec or understanding with anyone outside of the laboratory in either year. Through a pilot survey in Year 1 it was established that some students did take their Mini Specs home with them. In Year 2, a short Qualtrics survey (see supporting information) was deployed online two months after the laboratory session to enable enough time to gather reliable information on dissemination and outreach. Q1-Q6 gathered data on the extent and language of dissemination while Q7-Q9 probed the value of the spontaeous outreach for the audience and the student.

79 participants completed the survey in Year 2. It was found that 87.3% of students took the Mini Spec home and 65.2% of those who took the Mini Spec home shared it informally with the people around them. 36 of the participants disclosed the location of their spontaneous outreach (see Figure 6). Gauteng province, specifically South Africa's executive capital city Pretoria, had the highest frequency of instances of dissemination, this data came as no surprise given the location site of the laboratory experiment. Of interest is the truly portable nature of the Mini Spec that made the journey as far afield as Nelspruit (> 300 km / 180 mi) and Durban (> 600 km / 370 mi).

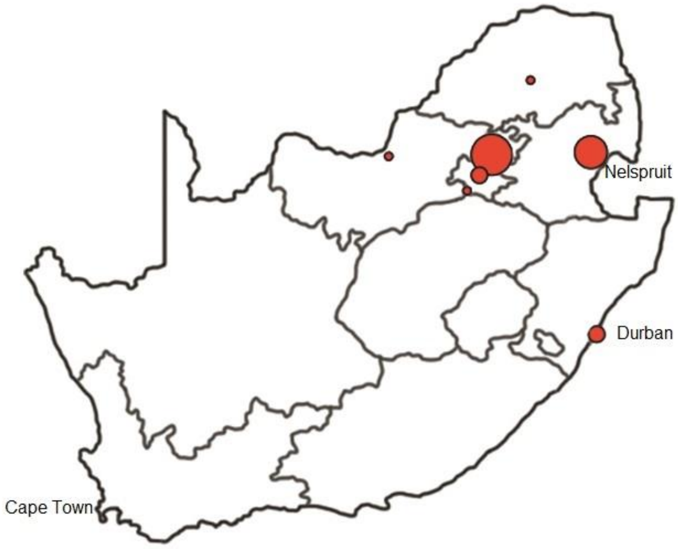


Figure 6. Map showing relative location frequency of Mini Spec dissemination based on 36 responses

The Mini Spec was shared with a wide range of people including friends, flat mates and family members. The interest of this audience, as reported by the participants, was very high (see Figure 7).

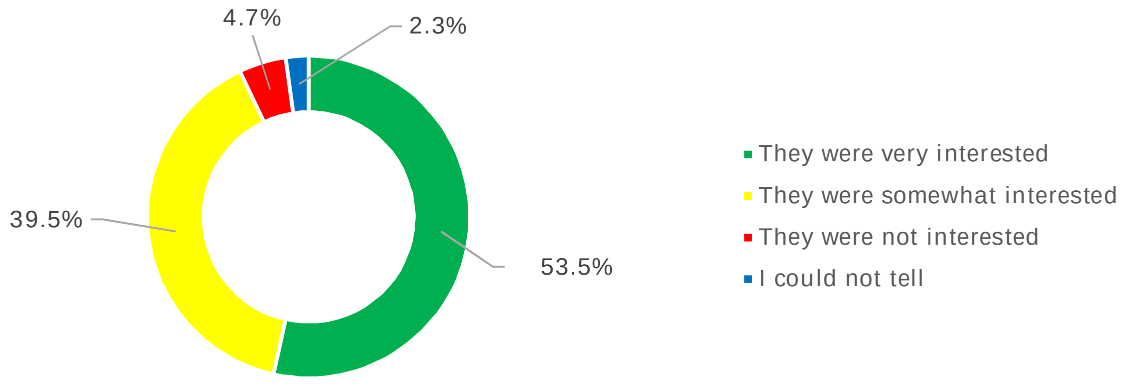


Figure 7. Response data from item Q5 of Qualtrics survey (What was their reaction to the Mini-Spec?)

South Africa's Constitution recognizes twelve official languages, including sign language. Almost half of the respondents (46.7%) reported English as the medium of spontaneous outreach. Six respondents selected “Other” and reported that the spontaneous outreach was bilingual or trilingual. Sign language was not mentioned by any of the participants. The remainder of the responses were fairly evenly split between the other official languages.

The Mini Spec met our goals of inclusive education as it travelled large distances and was shared in multiple languages with a diverse audience. We argue that these findings can act as evidence for the success of the spectral laboratory session in terms of creating interest and building confidence and a sense of agency in the students inside the laboratory, without which, this extent of dissemination outside of the laboratory would not have occurred.

The spontaneous outreach outside of the laboratory holds further value for both the students and their audience. Pratt and Yezierski developed a “Purposes for Outreach” framework that categorized the value of organized outreach initiates for the students, audience and insitutions.[15] Spontaneous outreach is different to organized outreach in terms of settings and support, however, the value of the informal learning experiences for students and their audience was still successfully explored using this framework. Written responses to Q8 and Q9 from the survey were coded according to the framework, for responses that consisted of more than a single word. The layout of the findings in

Table 2 and Table 3 are similar to that used by Pratt and Yezierski (2017) with representative quotes given for each described code.

Table 2. Coding of student responses on the personal value of outreach.

Purpose for Outreach	*Representative quotes from students*	*Frequency (n)*
Student enjoyment Affective goal of college students having fun, enjoying themselves, being entertained, etc.	"It was a fun way for me to interact with science and for it to really come alive" "Really enjoyed to show others what I have learned so they can maybe learn something from it as well"	7
Student learning Goal of student learning (including principles they should have already learned in the formal classroom)	"I have seen light as an everyday thing but never got to imagine how complex it is" "I got to explain how it worked which in turn refreshed my memory"	10
Students developing into scientists Talking to non-scientific audiences, appreciating the importance of service and helping the community, developing leadership and communication skills, and developing confidence in themselves	"I felt proud to be doing science" "It was nice for me to educate someone else about something I knew about and they knew very little"	9

The survey findings revealed a fairly even split between the Purposes for Outreach of student enjoyment, student learning and students developing into scientists. The frequency of the latter gives further support to the increased confidence and agency manifested by the students in conducting spontaneous outreach.

Eight of the Purposes for Outreach pertain to the audience.[15] The code 'Awareness of what science is and its place in the world' did not emerge in our data. 'Generating awareness/interest/curiosity' (see Table 3) is a combination of two of the original Purposes of Outreach: 'Awareness of and exposure to science' and 'Generating interest/curiosity'. Similarly, the code 'Awareness that science is fun' was merged with the code of 'Audience enjoyment' in Table 3, as no clear distinction could be made between the two codes given the detail of the responses in this study.

Table 3. Coding of student responses on the perceived value of outreach for their audience.

Purpose for Outreach	*Representative quotes from students*	*Frequency (n)*
Accessibility to science and who scientists are The focus is on scientists/chemists. The goal is to combat prejudice/stereotypes about who can be scientists and be role models in science.	"I think it was valuable in how it opened a window to the world of science as we can observe it"	2
Audience enjoyment Affective goal of the audience having fun, enjoying themselves, being entertained, etc.	"They described a science as being magic" "She did appreciate the display"	5
Audience learning Goal of audience learning (including developing scientific literacy skills)	"They did not know what a spec was before I showed them" "The person got to understand what light contains, and learned something about science"	8
Generating awareness/interest/curiosity Goal of getting audience interested in or curious about science. Introducing audience to science in general and/or exposing them to science, chemistry, or hands-on activities	"When I saw the interest in their eyes ...I was glad because I had made something" "They were very interested and found chemistry as an interesting subject"	9
Motivating for future study Goal of recruitment for future study (going to college, becoming the next generation of scientists, etc.)	"It was of great value because my little brother is interested in sciences"	1[a]

[a]The value of motivating a future scientist or professional cannot be quantified in standard terms, therefore this finding is still worth noting despite the low frequency.

Overall students did not see the value for their audience as being purely enjoyment and entertainment, but reported indications of authentic outreach, which is not just flashy student-led demonstrations but audience participation, motivation and learning.[24,25,26]

CONCLUSIONS

The Mini Spec was successful as a simple and low-cost laboratory experiment. Students were able to construct their own Mini Specs and use them to make hands-on observations of continuous and discrete spectra. When students were provided with further cognitive support in terms of construction references, the construction time was shorter and their performance improved. Confidence and agency was shown by students initiating unsolicited spontaneous sharing of the Mini Spec in their homes and communities. The extent of this outreach was broad in terms of language and distance, surpassing the extent of most formal outreach programs. This hands-on experiment showed how learning and enthusiasm can filter unobtrusively from the laboratory into communities, and the value it brings to both the students and their audiences.

Since many of the students on this program are the first generation in higher education i.e. they are the first member of their families or close relatives to study at a university, the benefits of spontaneous outreach can hardly be over emphasized. The outreach empowers students in terms of confidence and self-worth and makes science accessible to friends and family who would otherwise be poorer for it. These novice students become role models in their families and also develop a professional identity which may sustain them through the challenges of undergraduate study.

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