Shedding light on language difficulties in introductory spectroscopy

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General spectroscopy is known to be difficult for novice students due to its complex and abstract nature. In this study we used a first-year chemistry Mini Spec laboratory activity to uncover language barriers to student learning in spectroscopy. Analysis revealed that language barriers generated conceptual difficulties for English as Second Language (ESL) students. As well as demonstrating difficulty with understanding of the origin of spectral lines identified in prior research, this work surfaces previously unreported language difficulties which were characterized in terms of technical and non-technical language. These include observations that 'refract' and 'diffract' appeared poorly delineated for students, the teleological animism of 'jump' to describe excited electron transitions towards the ground state, and the non-technical term 'discrete' being difficult for students to understand and construct meaning for. In addition to this, students battled with the symbolic language required to depict the formation of spectral lines. Several solutions to the language difficulty are proposed including the re-sequencing of macroscopic, sub-microscopic and symbolic teaching and reconsidering the usefulness of certain non-technical terms for teaching and learning spectroscopy.

Introduction

Spectroscopy is the study of the interaction of light with matter to study atomic and molecular structure. As a core part of science curricula, the topic is usually taught from introductory level by means of studying visible light absorption and emission using activities such as refraction of light, line emission spectra, and flame tests to teach students the relationships between visible observations and sub-microscopic structure. This "atoms first" approach in chemistry curricula focusses on conceptual understanding, but provides significant challenges for students because it draws on a number of interrelated concepts, many of which are abstract (Rittenhouse, 2015).

Johnstone's Triangle

Johnstone's triangle, or the chemistry triplet, is a central framework for the teaching and learning of chemistry (Johnstone, 1991), as well as application in the teaching of both mathematics and physics (Johnstone, 2010). The triangle has three corners which represent thought levels or domains: the macroscopic (descriptive, tangible or visible), the sub-microscopic (interpretations, explanations and models of phenomena on the molecular level or smaller) and the symbolic where symbols, icons, equations and formulae are used as representational tools.

When comparing an expert in chemistry and a novice, it is the ease of movement between these levels that defines proficiency in chemistry (Reid, 2021b, Johnstone, 2010). In essence, the multi-levels which are key to understanding chemistry are also what makes chemistry difficult to learn when they are encountered simultaneously. Laboratory learning provides an environment where all three levels come together, however, learning may be undermined if students are cognitively overloaded (Johnstone, 2006, Johnstone and Wham, 1982).

Difficulties in understanding spectroscopy

A range of work has been reported that aims to further understand student difficulties with concepts related to spectroscopy. Bretz and Murata Mayo (2018) describe the development of a flame test concept inventory to measure student thinking about atomic emission, aiming to explore student understanding relating to tangible observations (colour of flame) and how that was represented symbolically through energy level diagrams. This explicit consideration of two domains relates to Johnstone triangle, and highlights why such concepts are difficult to learn: students are required to make ongoing connections between domains – what can be seen or is tangible, how this is represented, and what it represents. In their analysis, Bretz and Murata Mayo demonstrate persistent alternative conceptions relating to understanding of atomic spectroscopy, in particular conceptions about how atomic properties affect absorption and emission, and misrepresentations of atomic emission, with at least six common alternative conceptions of the latter identified, many attributed to alternative conceptions at the macroscopic/symbolic domain (Bretz and Murata Mayo, 2018).

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Similar challenges have been reported in physics and astronomy education. Bardar researched introductory college astronomy students' understanding of light and spectroscopy concepts, reporting persistent difficulty even after (traditional) instruction for topics, such as the relationships between wavelength, frequency, and energy, as well as the connection between spectral features and underlying physical processes (Bardar, 2006, Bardar, 2007). Related work on introductory physics students' understanding of emission line spectra, energy levels, and transitions revealed several incorrect ideas about these topics and the relationships between them (Ivanjek et al., 2015). These included associating lines directly with individual energy levels (rather than a transition) and using incorrect models for emission of photons, such as the energy level itself "dropping", rather than involving the electronic transition between levels.

The above work highlights two interrelated aspects that need to be considered regarding learning spectroscopy. The first is the conceptual understanding of spectroscopy. It is clear that there is a wide variety of alternative conceptions relating to understanding fundamental spectroscopy principles, and researchers and educators have sought to address these. The second considers how students transfer their understanding within a specific domain to other domains: for example, how they explain macroscopic observations using symbolic representations, and vice versa; and explicit in our context is the role of language capacity in achieving this goal. While work regarding conceptual understanding is well advanced, the impact of language capacity for novice learners – especially for those whom English is a second language – is less well understood. We aim to contribute to this understanding with this work. In doing so, we draw on two frameworks to underpin our study: Johnstone's triangle as already discussed as a means to document difficulties in understanding the topic of spectroscopy, and language literature to explore how these difficulties manifest for English as Second Language (ESL) learners.

Language

Language is seen as one of the most significant barriers to students' learning in chemistry (Wellington & Osborne, 2001). Added to this significance, the conversation about language in chemistry is constantly evolving as learning environments adapt to meet the needs of an increasingly diverse student body (Markic & Childs, 2016). So much so that a new language, "Chemish", has been proposed that negotiates both the technical and non-technical languages needed to fluently converse in, and thus understand, chemistry (Markic & Childs, 2016). The instructor needs to adapt and become aware of the language challenges facing students. In fact, pedagogical scientific language knowledge is now an essential part of the instructors' toolkit (Mönch & Markic, 2022).

Language and terminology

Rollnick (2000) remarked that both social constructivist theories and cognitive theories have had strong influences in understanding language acquisition. That is, language develops socially, but the majority of processing is individual. In terms of scientific language, Seah and Silver (2020) further this notion by explaining that students are socially enculturated with scientific language; however, scientific language must eventually become both a cognitive and representational tool for the individual.

English has become the universal language for communicating and building understanding in the sciences (Childs et al., 2015). Learning science when English is a second language (ESL) presents additional challenges: students may not have automatic access to meanings of words or extensive scientific vocabularies, and as such may have to rely on context to infer meaning (Mayer et al., 2014). Such construction of meaning creates additional cognitive load, which may overload the capacity of students who are most vulnerable (such as students who do not perform as well in assessments) (Fung and Yip, 2014, p. 1239). On the other hand, students may resort, or be coached, to learn vocabulary by heart. This rote learning or memorizing does reduce pressure on the working memory, and may be transient in the minds of the students as they are not able to assimilate the vocabulary into their long-term memory (Johnstone and Selepeng, 2001).

Whether students are ESL or first language speakers, proficiency in English is the key to conceptual understanding in science (Prinsloo et al., 2018). In fact, frequency of students' use of, and proficiency in, language was the strongest predictor of performance in high school science in South Africa, surpassing economic backgrounds and available infrastructure at home such as electricity and water (Prinsloo et al., 2018). This complements earlier findings by Cassels and Johnstone (1984) that the complexity of language placed an unwelcome load on students, which affected their performance in multiple-choice items, even in the case where students were considered first language English speakers. Subsequent work documented that processing of language places particularly large demands on the working memory of ESL students (Johnstone and Selepeng, 2001). Kelly (2010, p. 5) outlines some of the stages of processing that ESL students face in chemistry that may add to load: "Learners may also need more opportunities to think about concepts in the foreign language as well as time to internalize the formal language, express it in their own words, and translate their own words back into the formal language of chemistry".

Language and discourse

Rees et al. (2018) argue that all students are non-native speakers of chemistry: chemistry in itself is a second language which we all have to master. Experts in the field have mastered this discourse, however, it still presents significant difficulties to novices who need to be able to link the macroscopic, sub-microscopic, and symbolic levels of chemistry concepts (Taber, 2009). Rees et al. (2018) elaborate on this point, noting that significant challenges for novice learners emerge when students are tasked with moving between three levels of chemistry, often without explicit notice from instruction. They suggest that "each level has its own characteristic language, and a successful learner develops competence in and confidently inter-relates these three aspects." In order to be conversant in the language of science and to build understanding of scientific concepts, a general language proficiency is required, and a basic proficiency is needed before any thinking or understanding can occur (Childs et al., 2015, p. 421). Even in situations where students have a general English proficiency, language difficulties arise when common terms are used in a scientific context and their meaning changes (Oyoo, 2007).

We focus on the two main types of language terminology used: technical (T) and non-technical (NT) terminology as first described by Gardner (1972), expanded on by Oyoo (2007, 2017) and revisited in more detail by Quílez (2019). This classification tool for language difficulties will be used to frame the results of this study. In Table 1, the main distinctions and relevant types of technical and non-technical terminology are briefly explained with examples from emission spectroscopy in *italics*.

In our research, language came to the fore as a major barrier to students' learning in spectroscopy. Spectroscopy is a complex and abstract topic, as such technical terminology was anticipated as a barrier for ESL students. Moreover, we sought to understand the facets of this barrier that were also non-technical in nature and thus challenging for an instructor teaching spectroscopy to anticipate. By combining the technical and non-technical terminology findings a substantial contribution may be made to pedagogical scientific language knowledge in this foundational topic.

Research question

The primary aim of this study is to identify language difficulties as they arose for novice first-year ESL students during a laboratory exercise on spectroscopy and emission spectra. While we are focussed on our context of primarily ESL students learning spectroscopy in South Africa, we add to the broader literature about the difficulties of technical language acquisition and use more generally. Specifically, we intend to address the following research question:

- What language difficulties emerge for ESL students when explaining their conceptual understanding in introductory spectroscopy?

Based on our findings this work also intends to make recommendations for improving pedagogical scientific language knowledge in spectroscopy.

Methodology

In this study, the laboratory setting provided students with the opportunity to engage with a spectral tool and its components whilst collaborating with peers and staff. Using a mixed methods design, data were collected prior to the laboratory exercise, during the laboratory exercise and after the laboratory exercise. Language difficulties were tracked over time to pinpoint the type of language difficulties which emerged, persisted or were mitigated during the laboratory exercise.

Data was collected over several cycles spanning three years. Design-based research was employed to fully support students' laboratory learning and at the same time enabled the researchers' to develop insights into the language barriers students may be facing (Mundy, Potgieter, & Seery, 2024). The

Table 1. Comparison of terminologies used in the teaching and learning of science

Technical terminology	Non-technical terminology
Defined broadly as "technical words or terminologies specific to a science subject; these may also be referred to as technical terms, scientific terms/ terminology, science terms, or simply science words" (Oyoo, 2007, p. 232)	Defined broadly as everyday words that take on a scientific meaning when used in scientific disciplines (Oyoo, 2007).
T1. Discipline specific *e.g. photon, quantization* These are either long standing or newly coined terms that were created deliberately within the discipline to describe new phenomena (Quílez, 2019). Due to the nature of science, the extent of scientific vocabulary is constantly growing.	**NT1. Non-technical terminology in scientific contexts** *e.g. excited* These are common words to the language of instruction that take on a new, discipline-specific meaning when used as part of the language of science (Oyoo, 2017).
T2. Terms with evolving meaning *e.g. atom* The meaning of the word atom shifts with time or the meaning of the word changes based on the context, in this case the model of the atom in question at a particular time or for a particular application (Quílez, 2019).	**NT2. Teleological terminology** *e.g. share* The use of simplified terms that result in personification, animism or anthropomorphism in an attempt to improve student understanding (Taber and Watts, 1996, Quílez, 2019)
T3. Symbolic language *e.g.* e^{-}, λ, H, *energy diagrams* Chemists use a specific symbolic language to explain the links between macroscopic observations and sub-microscopic representations (Rees et al., 2019, Taber, 2009)	

nature of the study's design allows for greater confidence in the findings presented.

Context of the study

This study was set in an academic development programme at the University of Pretoria, South Africa. Academic development programmes, in the form of extended or augmented programmes, offering holistic development and support, have become prevalent in South Africa to facilitate access to tertiary education for students who would otherwise not qualify for admission (Shay et al., 2016). Students on programmes such as these are mainly second language English speakers (ESL) from diverse backgrounds with limited laboratory experience (Rollnick et al., 2001).

General chemistry is a semester-long course in the first year, first semester of the academic development programme. This course has both a taught component, which is highly scaffolded and learner-centred, and a compulsory laboratory component. The study took place in one of six compulsory three hour practical sessions. Class sizes were typically 450 students, with students completing labs in cohorts of about 50.

Sample description

In this study, we describe our cohort as ESL due to the prevalence of this term in chemistry education language literature. The definition of ESL may not fit all of the students in this study (English may be their third or fourth language), but from institutional data it is known that more than 80% of the student cohort in does not speak English as their home language even though they are proficient in everyday language use.

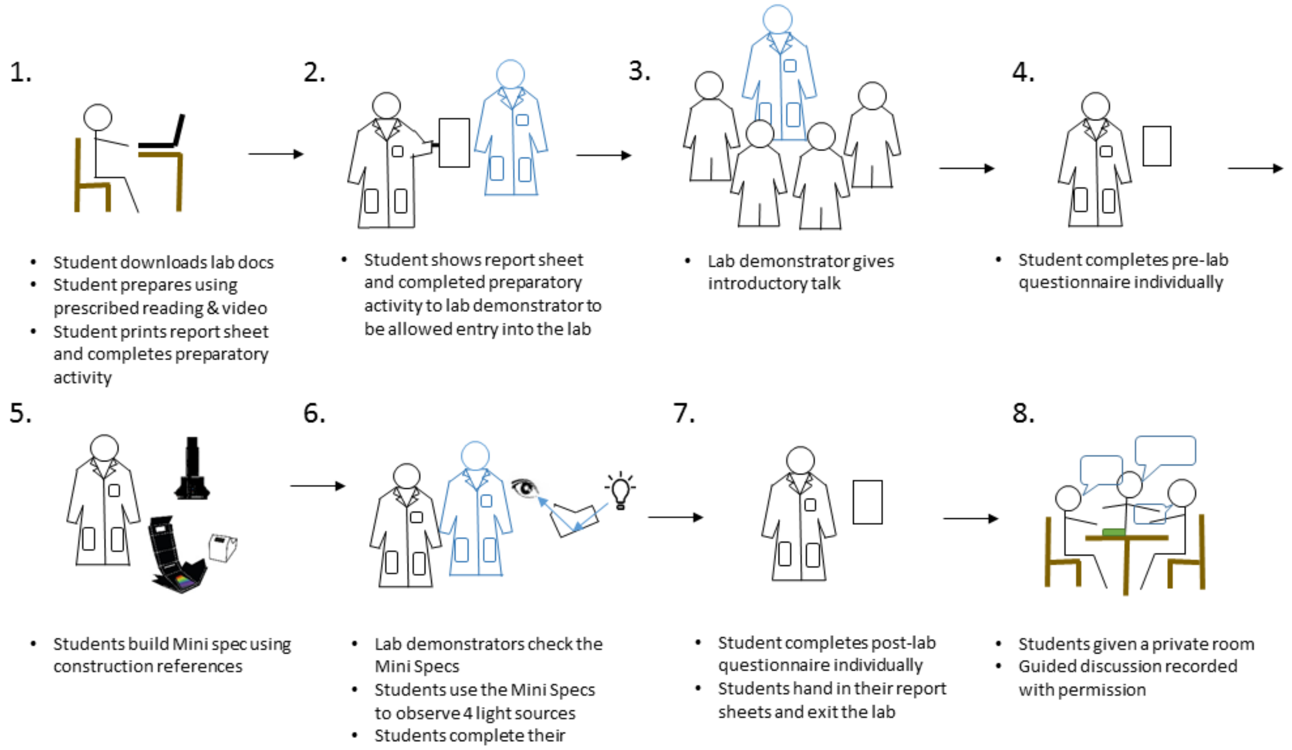
Potential participants were purposefully approached by the demonstrators (senior students who assist in the lab) based on the time required to complete the Mini Spec laboratory experiment. Students were invited to participate from those who had finished early, those who finished comfortably within the time, and finally those who struggled to complete the exercise. This sampling technique was used to arrive at a representative cross-section of students using the pace of completion as a proxy for language proficiency and academic ability. Two sample groups were formed out of a total enrolment of 409 students, where *n* = 18 and *n* = 31. The only distinguishing factor between the groups was the just-in-time change of one term in one of the data collection tools.

Ethical clearance was granted by the corresponding author's institution for this research (180000144). All participants provided informed consent.

Laboratory setting

Before the introduction of the Mini Spec laboratory exercise in this study, there was no practical component to support learning in the abstract and complex topic of spectroscopy and emission spectra. The design of the Mini Spec activity and associated Report Sheet was informed by cognitive load theory (Mundy & Potgieter, 2020): instructions and layout were clear to manage extraneous load, the task was pitched at a level of difficulty to be cognisant of intrinsic load, and purposeful scaffolding was used to guide students' learning throughout the laboratory exercise to enable germane load and processing.

The Mini Spec is a simple device assembled from a template cut out of thick paper with a slit and a mounted wedge of CD to diffract incoming light. The Mini Spec was used to observe four



1.
- Student downloads lab docs
- Student prepares using prescribed reading & video
- Student prints report sheet and completes preparatory activity

2.
- Student shows report sheet and completed preparatory activity to lab demonstrator to be allowed entry into the lab

3.
- Lab demonstrator gives introductory talk

4.
- Student completes pre-lab questionnaire individually

5.
- Students build Mini spec using construction references

6.
- Lab demonstrators check the Mini Specs
- Students use the Mini Specs to observe 4 light sources
- Students complete their

7.
- Student completes post-lab questionnaire individually
- Students hand in their report sheets and exit the lab

8.
- Students given a private room
- Guided discussion recorded with permission

Figure 1. Overview of the sequence of the laboratory exercise

types of light spectra, incandescent, sunlight, energy saver, and fluorescent. The Report Sheet guides students in exploring the components of the Mini Spec and recording observations, with the goal of building understanding of the significance of spectral phenomena.

In order to facilitate student preparation, pre-laboratory activities were incorporated into the process (Agustian and Seery, 2017). Before entering the laboratory, students prepared for the laboratory experiment using an instruction sheet, prescribed reading, and watching prescribed videos (Figure 1, step 1). Students had to complete a pre-laboratory activity built into the Report Sheet before they could access the laboratory (Figure 1, step 2). The completion of the pre-laboratory activity was verified by demonstrators. The demonstrators then led talks with students before the laboratory exercise commenced, this talk included relevant health and safety information, such as how to hold scissors for cutting complex pieces and how to safely observe sunlight (Figure 1, step 3). Next students constructed their Mini Specs and submitted them to the demonstrators for verification before they begun to make observations (Figure 1, step 5). After completing the laboratory exercise, students were expected to hand in their Report Sheets for grading upon exist of the laboratory.

Data Collection

Four data sources were analysed in the study to establish areas of potential language difficulties. Firstly, students' diagrammatic responses to the pre-laboratory activity were collected. The pre-laboratory activity was designed to strengthen students' understanding of the formation of spectral lines, which was already taught during lectures. Pre-laboratory activities are typically used to reduce cognitive load and thus increase working memory during the laboratory session, an environment which is already viewed as complex (Agustian & Seery, 2017; Johnstone & Wham, 1982). The pre-laboratory activity required students to answer the following question using an appropriate diagram, showing their reasoning with relevant chemical symbols: "***If an electron in Helium is excited to the n = 4 level, how many emission lines will be seen in the emission spectrum?"*** This pre-laboratory activity had to be completed before students were allowed to enter the laboratory (see step 2, Figure 1).

Students' Report Sheets were the second source of data collected. These Report Sheets contained five guided questions: the first two questions dealt with students' understanding of the focusing slit and the diffractive grating in the Mini Spec. The third and fourth question were designed to make students explore the type of spectra observed and conceptualise what is meant by discrete and continuous spectra. The final question aimed to assess students' understanding of the link between the brightness of spectral lines and their probability of occurrence. Students answered these questions during the laboratory and handed them in to be marked at the end of the session (see step 6, Figure 1).

The third data source were the pre-laboratory and post-laboratory questionnaires. The pre-laboratory questionnaire was given to each student in the laboratory before they commenced work in the laboratory (see step 4, Figure 1). The pre-laboratory questionnaire consisted of one multiple-choice question and an open-ended follow-up question asking students to give reasons for their choice. This two-tier approach was purposeful in its design as the follow-up question allowed students to construct their own explanations using technical or non-technical language, therefore language difficulties and their link to conceptual difficulties could be identified. The post-laboratory questionnaire again included the same multiple-choice question, and an open-ended follow-up question that asked students to give reasons for their current choice compared to their choice in the pre-laboratory questionnaire (see step 7, Figure 1). Students were allowed as much time as required to complete the questionnaires; usually requiring five minutes.

The multiple-choice item which was chosen for this study represents a cumulative assessment tool proposed by Ivanjek, et al. (2015) after a large-scale study which sought to identify student difficulties with atomic emission spectra over four years with approximately 1000 participants (see below). The design of the item was purposeful in including known conceptual difficulties around the inter-related concepts of spectral lines, photon energies, and energy levels as distractors (Ivanjek et al., 2015).

Choose the option you feel is the most correct. Spectral lines are formed when:

A. An atom emits an electron to become more stable
B. An electron jumps between energy levels in an atom and emits a photon
C. A photon drops between energy levels emitting different wavelengths of light
D. An atom absorbs a photon
E. One energy level drops to the energy level directly below it and emits a photon

Give reasons why you chose this option compared to other the options available.

Figure 2. Multiple-choice item used as pre- and post-lab questionnaire

The final data source came from recordings of students' post-laboratory discussions. Post-laboratory discussions took place in small groups of 2 to 5 students. All students from sample 1 and 2 chose to participate. Students were conveniently allocated to groups by the laboratory demonstrator as they completed the laboratory exercise (see step 8, Figure 1). The post-laboratory discussions were guided by a four question collaborative activity. The first two questions probed the "most important observation of", and, "most important observation from" an energy saver globe. The third and fourth questions were a repeat of the post-laboratory questionnaire, the difference being that students should try arrive at a consensus instead of answering individually as in the pre- and post-laboratory questionnaire.

Analysis

Students diagrammatic responses to the pre-laboratory activity were analysed in terms of the correctness of their answer (students should have concluded 6 emission lines were possible). The types of symbols the students used in their answers was evaluated (be it accepted symbols or students' own representations). Additionally, the frequency of use of particular symbols along with consistent omissions of other symbols were also noted.

Reflexive coding using Atlas.ti was used to analyse the qualitative data from the Report Sheet and the written responses to the pre- and post-laboratory questionnaires, that is, the researcher constantly re-aligned the coding to the aims of the study whilst still allowing for insights to emerge. Initially the researcher immersed themselves in to data and came up with potential codes, revisiting and reflective on the codes was done in analytic coding memos used by the researcher to track the evolution of each code. This process resulted in a coding rubric in which students' understanding was explored according to each question and the student responses were then coded as good, partial, and poor understanding of the concept at hand (see Tables 2 and 4). In creating the coding rubric, particular notice was given to explanations that suggested that student understanding was hindered by language difficulties. After two rounds of rubric refinement, excellent agreement was obtained between codes assigned by two independent coders (Spearman's rho rank correlation coefficient, r_s >.839, p < .000, df = 39).

A four quadrant descriptor system was used to quantitatively analyse the multiple-choice responses based on whether students answered correctly (C) or incorrectly (I): CC for students who were able to select the correct answer in both the pre- and post-laboratory questionnaire, IC for those who were incorrect in the pre-laboratory but corrected their answers post-lab, II for those students who were incorrect in their understanding of the formation of spectral lines both pre and post-lab; and, finally, CI, for those students who initially selected the correct answer but followed that with an incorrect selection in the post-laboratory questionnaire.

Representative vignettes of the recorded post-laboratory discussions are presented to triangulate findings from the questionnaires and the Report Sheets. The post-laboratory discussions served as an additional tool used by the researcher to gain insights into the linguistic barriers experienced by students in spectroscopy. The vignettes are given verbatim so that the reader can evaluate the strength of the claims made.

Results

The language difficulties which students faced have been grouped according to the types of terminologies used in the teaching and learning of science (see Table 1). Compelling evidence was found for four of types of terminology (T1, T3, NT1 and NT2), however, no evidence of language difficulties was found for word types with evolving meaning (T2). This may be because words with evolving meaning are not appropriate in the curriculum for first-year academic development programme students and are thus absent from the data. Language difficulties with technical terminology (T1) were anticipated, however, difficulties with non-technical terminology (NT1 and NT2) emerged as noteworthy alongside students' difficulties with constructing representations of emission line formation (T3). Results for sample 1 and 2 are combined throughout the results section, as there was no notable difference between the responses, except in the case of NT1.

T1. Discipline specific terminology

During construction a small wedge of CD is mounted in the Mini Spec, which has two functions. Primarily, it acts as a diffraction grating, splitting incoming light into its component wavelengths. Since the CD has similar capabilities as a costly transmission/diffraction grating, it was used as an inexpensive replacement (Wakabayashi et al., 1998). The secondary function of the CD is to reflect dispersed wavelengths so they can be viewed through the eyehole.

In the Report Sheet, a guided question was used to help students construct meaning for the purpose of CD and retrieve relevant discipline specific term, diffract, to describe this. The question, ***"How is the piece of CD in your Mini-Spec similar to a prism?"*** intended to prime the perception filter and stimulate feedback from the long-term memory. The phrasing of this question links the current Mini Spec laboratory experiment back to high school demonstrations and familiar illustrations of prisms splitting white light into rainbow colours. In Table 2, a response was coded as 'Good understanding' when a student used the discipline specific term, ***diffracts***, or explained that the light from the source would be split or separated into its components.

The coding of responses was thought-provoking as many students used the word ***refracts*** in place of ***diffracts***. Refraction is also a discipline specific technical term defined as the bending of light in different media such as the transition from water to air, or air to glass to air as in a prism. In the case of a prism, the refraction results in the splitting of light into its components but refraction does not always result in splitting. The wedge of CD diffracts the light into its components due to its striated (grooved or lined) surface. When analysing the students' use of ***refracts*** in their written explanations, such as the response "the CD refracts the white light ***into seven different colours***" (P29), the intended meaning of refracts coincided with diffracts, therefore such a response was agreed to be coded as 'Good understanding' even though it was not scientifically accurate (Table 2).

Reflect is a term that is non-technical, however, in a science setting it has a very specific meaning. If a student used this term to describe the purpose of the wedge of CD, the code 'Partial understanding' was used. The non-technical term reflect does not have any implication that there was an interaction of incoming light with the surface of the CD, just that there was a change of direction of the light.

Table 4. Coding of students’ written Report Sheet responses on the purpose of the wedge of CD.

Code	Representative written responses	Frequency (n = 47*)
Diffraction, Poor understanding Students attribute a completely inappropriate purpose or phenomenon to the CD. Alternately, the perceived purpose of the CD may be just be the place where spectra may be viewed.	“Also, the shape of the CD was cut in to” P5	1
Diffraction, Partial understanding Students only acknowledge the reflective property of the CD not the diffractive purpose. Students may see light as bouncing off the surface of the CD, but do not acknowledge the interaction of light with the striated surface of the CD, causing the reflection of light at multiple angles or “diffraction”. Note: reflection may have angles other than 180^0.	“A piece of CD is similar to a prism because once light shines on it, it reflects the colour spectrum” P55 “Both the prism and the CD are light reflectors” P1 “It is similar because it reflects light and allows all or most colours to be seen” P31	12
Diffraction, Good understanding Students acknowledge that the beam is diffracted, split or spread out into its components when it interacts with the surface of the CD. “Defract” was acceptable as this appeared to be a common misspelling of diffract. “Refract” was only accepted based on the given explanation.	“It diffracts and splits light into its component colours” P27 “It refracts the light in the same way that a prism does by separating the light into its different colours” P42	34

*several responses (n) were not coded due to missing data or the quality of the photocopied hand-written Report Sheets

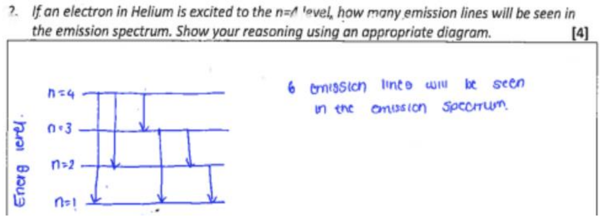
A new term also emerged regularly in students’ explanations, ***defract***. This term does not exist as either technical or non-technical. Having carefully checked the context of the responses, we conclude that ‘defract’ is a misspelling of the word diffract and thus a simple mistake, therefore it was coded as ‘Good understanding’.

T3. Symbolic language

Students’ understanding of the mechanism of the formation of spectral lines is a key learning outcome in undergraduate chemistry or physics courses that include spectroscopy in the curriculum (Savall-Alemany et al., 2016). In fact, according to Ivanjek et al. (2015a), if students understand the concept of the formation of spectral lines, it is likely that they have grasped many other spectroscopic concepts.

Communicating the formation of spectral lines is often done using symbolic language, especially if a diagram is called for. In answering the question, students relied on what they were taught regarding the Bohr model of the hydrogen atom. Students needed to apply what they had learnt about spectral line formation in the hydrogen atom and realise that the ground state for the electrons in helium would be the same as for hydrogen (n = 1) as both elements only have electrons in the 1s orbital in the ground state. This often required referring to the periodic table and consulting with staff.

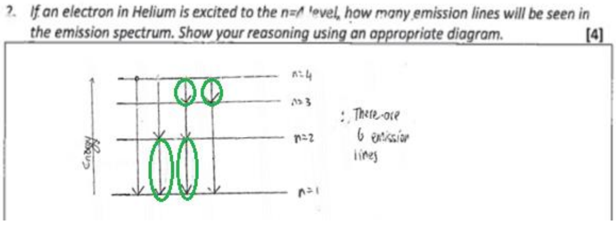
The majority of the students’ answers showed that the students drew sub-microscopic representations that reflected the principal energy levels in the atom along with symbols of possible downwards transitions that would result in six unique emission lines (see Figure 3 and Figure 4).



?. *If an electron in Helium is excited to the n=4 level, how many emission lines will be seen in the emission spectrum. Show your reasoning using an appropriate diagram.* [4]

6 emission lines will be seen in the emission spectrum.

Figure 4. A student’s response to the pre-lab activity (P41)



?. *If an electron in Helium is excited to the n=4 level, how many emission lines will be seen in the emission spectrum. Show your reasoning using an appropriate diagram.* [4]

∴ There are 6 emission lines

Figure 3. A student’s response to the pre-lab activity (P51). Here the student acknowledged 8 possible transitions that would still result in only 6 emission lines.

The diagram was supposed to be a means by which students communicate their understanding of the formation of spectral lines. Clearly, students incorrectly see the transitions or pathways as the emission lines themselves. Many students omitted electrons in their drawings along with photons, meaning it is unclear what is transitioning and what (if anything) is being released. Table 3 shows the frequency of symbols used in the diagrams, with almost all students showing downward transitions with an arrow. Of these 42 students, only 16 showed electron(s) on their diagram as spheres or using the more conventional symbol e^{-}. This means that students either are unclear on the mechanism of spectral line formation or they do not invest in the accepted symbolic representations required to effectively communicate their understanding to a scientific audience. In fact, only 1 of the 47 students included both electrons and a photon in their diagram.

Table 1. Frequency of students' use of symbols in the pre-laboratory activity (*n* = 47*).

Symbol	Meaning	Frequency
↑	Upward transition (incorrect)	5
↓	Downward transition	42
●	Electron	13
e^-	Electron	3
	Photon	2

*several responses were not coded due to missing data or the quality of the photocopied hand-written Report Sheets

NT1. Non-technical terminology in scientific contexts

Of importance was developing students' ability to apply the non-technical terms 'discrete' and 'continuous' to their macroscopic laboratory observations. The wording of the Report Sheet question scaffolded student thinking in terms of the type of spectra observed; whether it was discrete or continuous:

Compare natural light (d) to the artificial light sources (a,b,c) in terms of the colours observed with your Mini Spec and the type of spectrum observed. Fully explain these findings.

Students' responses to this question from samples 1 and 2 were coded as poor, partial, and good in their ability to both classify *and* explain their classification of the spectra (see Table 4).

Upon further investigation of students' responses, it was revealed that many students classified as having partial understanding manifested an incorrect alternate conception of spectral line classification. Students saw continuous spectra to mean that all of the colours were visible, and discrete to mean that only some of the colours were visible in the spectra. This is not true, a discrete spectrum may contain all seven of the rainbow colours; the hallmark of a discrete spectrum is the banding of light, not the number of colours seen. Students appear to have constructed their own meaning for the terms continuous and discrete based upon a false dichotomy, for example, yellow emission lines are often missing in discrete spectra. Students' constructed word-meaning and thus built concepts for themselves. These constructed word-meanings were flawed and do not allow for the next conceptual step: the revelation of quantized energy levels within the atom based on discrete light emissions for the excited electron.

This finding can be corroborated with the vignette from the collaborative post-laboratory activity below. Here it can be seen that Student 2 answers Student 1 with a flawed definition of discrete spectra based on flawed constructed word meaning. Student 3 tries to correct this but is unsuccessful as the Student 1 proceeds to build their misconception by conflating discrete or quantized spectra with the intensity of emissions within a spectrum. Student 3 does not attempt to correct the group again, and remains silent on this point.

Table 4. Coding of students' written responses on the classification of spectra.

Code	Representative written responses	Frequency (*n* = 46*)
Continuous vs. discrete, Poor understanding Students give an inappropriate response. Students may use the terms discrete or continuous, but there is no indication from their observations or discussion that the terms are used correctly. Students may also just repeat that sunlight produces a rainbow, out of context.	"Artificial lights can be used to replace a colour" P52 "The energy saver shows a continuous spectrum of light" P53 "In the artificial light there were more dim array of colours indicating a decrease in kinetic energy" P19	8
Continuous vs. discrete, Partial understanding Students use the terms discrete or continuous correctly to record their observations, but they do not elaborate on the meaning of the terms or may assign incorrect meaning. Students think discrete means the absence of some colours and do not see discrete as referring to definite bands.	"Natural light contains all of the spectrum while artificial lines do not contain all of the colours" P17 "Artificial light contain a discrete spectrum" P27 "Natural light is continuous, 2 of the 3 artificial light sources are discrete" P42	32
Continuous vs. discrete, Good understanding Students show a good understanding of the classification of observations, even if they do not use the terms specifically. Continuous is seen as "all" of the colours in the visible spectrum or a blend or blur of all of the colours. Discrete lines are described as lines or bands with dark spaces.	""Natural light has a continuous spectrum – contains no boundaries, but incandescent is also continuous. Whereas artificial lights have a discrete spectrum which means that it has bands or boundaries" P21 "The artificial light sources displayed a discrete spectrum, which was like a colour separated by a dark solid line" P5	6

*several responses (n) were not coded due to missing data or the quality of the photocopied hand-written Report Sheets

Student 1: What is the difference between discrete and quantized?
*Student 2: Discrete, **it doesn't show all the colours.***
Student 3: No, it (quantized) has the same meaning as discrete
Student 1: Some bands are brighter than others, so they are quantized.

NT2. Teleological terminology

After having shown a demonstrator the pre-laboratory activity and entering the laboratory, students were given the opportunity to fill in a pre-laboratory questionnaire. This single multiple-choice item assessed students understanding of the formation of spectral lines (see below) an open item was also included to interrogate students' reasoning. After completing the experiment, students were again given the opportunity to complete a post-laboratory item that posed the identical questions. When classifying students' answers, the following four quadrant descriptor system (CC, IC, II, CI) was used as discussed previously (Table 5).

Table 5. Students' responses from sample 1 (n = 18) to the questionnaire item, "Spectral lines are formed when"

		Post-laboratory	
		% Correct (n)	% Incorrect (n)
Pre-laboratory	% Correct (n)	**CC** 61% (11)	**CI** 6% (1)
	% Incorrect (n)	**IC** 22% (4)	**II** 11% (2)

The four IC students exhibited partial understanding in the pre-laboratory questionnaire by acknowledging that transitions between levels result in emissions, but selected the photons as those transitioning (question option C), not the electrons (question option B). However, in the open item of the post-laboratory questionnaire, all four IC students from sample 1 acknowledged that they realised that it was the electron that must transition **downwards** for energy to be released.

Participant 48 written responses

Pre-laboratory:	A photon is a package of light and as it passes between energy levels
Post-laboratory:	When the electron moves down between energy levels, light is observed

Participant 57 written responses

Pre-laboratory:	When a photon drops between different energy levels the energy increases. A photon gives up an energy level and energy increases (released)
Post-lab:	My answer changed because I realised when an electron jumps a certain amount of energy levels down, it releases energy…

This is further corroborated by a vignette from a group discussion in sample 1:

*Student 4: But it (the electron) is going to fall unless there is too much power to eject it. It **is always going to fall**.*
Student 5: Okay it's going to fall. Let's say, if it receives energy, it is going to jump but then if it loses energy it is going to go back. So, this statement it says only jump. But you know an electron can lose energy and go back.
Student 4: But when it jumps it doesn't really emit anything does it?
Student 5: It does emit, some energy will be emitted.
Student 4: Because the energy increases as you go up?
*Student 5: But then I think the photon drops because a photon is a pocket of light. So, whether it (the electron) **jumps**, the photon will always **drop** between levels.*

The simple non-technical terms jump or drop appear to have a large impact on students' choices. A pre-occupation with the directionality of the teleological and animistic term jumps altered choices around the concepts of electron transitions and photon emissions. A decision was made to adjust the questionnaire wording for the repeat of the laboratory session from which sample 2 was drawn so that option B and C would become more similar for students: the word jumps was replaced with drops (see Figure 5).

Choose the option you feel is the most correct. Spectral lines are formed when:

A. An atom emits an electron to become more stable
B. An electron drops between energy levels in an atom and emits a photon
C. A photon drops between energy levels emitting different wavelengths of light
D. An atom absorbs a photon
E. One energy level drops to the energy level directly below it and emits a photon

Figure 5. Improved multiple-choice item used as pre- and post-lab questionnaire

Six students from sample 2 fell into category II with most clinging to option D (see Table 6), making this a popular distractor and further affirming students' difficulty with the concept of spectral line formation. Astonishingly, the decision to replace jumps with drops led to a higher prevalence of students choosing the correct option in the pre-laboratory questionnaire. This finding signposts the importance of language and terminology chosen by the instructor, even if it may appear as inconsequential.

Table 6. Students' responses from sample 2 (n = 31) to the questionnaire item, "Spectral lines are formed when"

		Post-laboratory	
		% Correct (n)	% Incorrect (n)
Pre-laboratory	% Correct (n)	**CC** 74% (23)	**CI** 3% (1)
	% Incorrect (n)	**IC** 3% (1)	**II** 19% (6)

Discussion

The Mini Spec was a physical artefact in a hands-on spectroscopy activity and was complemented by a guided Report Sheet. The Report Sheet was designed to stimulate recall of prior knowledge and to facilitate meaning-making, both socially and individually. The hands-on (macroscopic) activity was aimed to relate the prior learning to thinking at sub-microscopic and representational levels, and as such, difficulties that emerged could be identified, as students were tasked with making their thinking explicit through requiring explanations. In the context of considering language, difficulties were anticipated for students when accessing and using technical terms that were discipline specific and symbolic respectively, however, difficulties with non-technical terminology, especially teleological terminology, and the ease with which these can be overcome is of great interest.

Reflections on symbolic language

Symbolism is one of three domains in the chemistry triplet (Johnstone, 1991). The symbolic domain was also known as the representational knowledge domain because it relies on symbols, equations, formulae, diagrams and graphs to convey chemistry understanding in a certain topic. Taber (2009) argues the symbolic provides the resources for the representation and communication of chemical concepts. Talanquer (2011) also points out the interconnectedness of the symbolic and the submicroscpic domains, especially when explanatory models are drawn. In this research, symbolic knowledge was taught prior to students' laboratory experience. Students were familiar with the Bohr model, photons and electrons before the idea of transitions between energy levels was discussed. This research has firstly demonstrated results consistent to those previously reported regarding the inadequate or misunderstood origin of spectral line formation (Ivanjek et al., 2015). However, our particular focus on language has surfaced new findings relating to language and learning spectroscopy, and we describe each of these in turn, below.

Reflections on refract, diffract and defract

The discipline specific terminology relating to the field of optics (refracts, reflects, diffracts) presented challenges to students in describing the function of the wedge of CD within their Mini Specs. Many students were not able to access prior knowledge of these concepts successfully, leading to the proposal that these concepts were not understood. This topic is also presented in physics teaching, but there is evidence that students are poor at transferring knowledge from one domain to another (Potgieter et al., 2008). The lack of readily available prior knowledge may have led to students formulating their own terminology such as the use of "defract", or possibly, the sheer load created by attempts to recall information which was poorly stored in the long-term memory resulted in pedestrian spelling mistakes "defract" vs. diffract.

The technical terminologies in this instance have additional difficulties in that they look similar in appearance, "look-alike", and sound similar in pronunciation, "sound-alike" (Oyoo, 2017, Cassels and Johnstone, 1984). Additionally, these technical terms come from the same "word family" of the optics topic and therefore students may conflate their meaning (Rees et al., 2018), differing from words that merely "sound-alike" and "look-alike" but are unrelated in their meanings.

It is likely that students lacked appropriate prior knowledge to distinguish between (or apply) the terms of refraction and diffraction. This interpretation corresponds with "language fluency" referred to by Rees et al. (2019) where students require the language skills and conceptual foundations to discuss chemical phenomena at all levels of the chemistry triangle (Taber, 2013). A review of solutions details pedagogical strategies focusing on language and literacy to overcome difficulties with understanding (Oyoo, 2007). An appropriate future design decision may be to engage with the words more actively in the lectures and tutorials before students attempt the practical, or to build in a pre-laboratory activity that highlights the differences and similarities in these words (such as with the use of an animation or video).

Jumping and dropping electrons

Language as a difficulty, made a reappearance in the non-technical terms, "jumps" and "drops" used when describing electron transitions. This was a surprising finding as both terms are relatively simple non-technical terms that any student with a basic proficiency in English would be familiar with. In the chemistry classroom practitioners often refer to electrons jumping upwards and downwards between energy levels, depending on whether excitation or a transition towards the ground state is occurring. The difficulty here lies that we are animating the electron to try to facilitate student learning on the sub-microscopic level (Taber and Watts, 1996, Quílez, 2019), but, an electron does not have arms and legs; it does not jump, nor does it drop like a ball. The terms we use to animate the electron – although they seem clear enough – provide a source of confusion for ESL students who only see jumping in an upwards direction; their knowledge structure around this term is limited. The animism of "jumping" electrons creates cognitive dissonance in the minds of some of the ESL students; the conflict forced them to reject the correct answer, ***Spectral lines are formed when: An electron jumps between energy levels in an atom and emits a photon***, in favour of a flawed mechanism of spectral line formation.

By substituting the term "jumps" with the term "drops", all the options in the multiple-choice read in a similar fashion and most students in the second sample were able to select the correct option both pre- and post-laboratory experience. As educators, instructors and designers of learning materials and classroom activities we tend to favour language that simplifies concepts for students. It may be beneficial to leave behind such animisms which lead to teleological reasoning in favour of technical terms like transition which have no directionality connotations for ESL students.

Discretely difficult

Emission spectra are classified as either discrete or continuous, strictly speaking these are non-technical terminologies used in the scientific context. Most artificial light sources like energy saver globes give a discrete spectrum which is unique to the materials it was made of. As students observed, white light from incandescent bulbs and natural sun light result in a continuous spectrum. In describing and building an understanding of the characteristics of emission spectra, the language starts as non-technical to describe the macroscopic laboratory observations (discrete vs. continuous) but must eventually give way to technical terminology that carries deeper scientific meaning and theoretical implications in terms of the electronic structure of the atom (quantization of energy levels). However, even the starting point in non-technical terminology is challenging, especially from a novice ESL perspective.

'Discrete' is the term frequently used to describe a spectrum consisting only of small or isolated segments of the electromagnetic spectrum (a line spectrum). The term "discrete" is no longer as common in the modern vocabulary as synonyms like separate or isolated. Furthermore, discrete is not as common in the modern vocabulary as its homophone, "discreet", adding further strain to the cognitive scaffolding of the meaning of discrete in a scientific context. Additionally, instructors often equate the words discrete and quantized, this adds even more confusion in the mind of the learner, as the technical word quantized has no meaning outside of the scientific realm.

In this study, we tried to enable students to build their own definitions of the terms discrete and continuous, however, the lack of vocabulary knowledge around the non-technical term discrete allowed for students to form incorrect alternative conceptions of what the term discrete actually means. As the term discrete does not actually feature in the everyday modern vocabulary but it is still continued to be used in scientific communities, meaning that students have little or no prior knowledge to work with. If the word discrete has little meaning to ESL students in everyday use, students have to infer meaning from the laboratory exercise. This difficulty is a difficulty that is hidden from experts in the field who have either constructed their own schema for the meanings of such words or who have had the benefit of a more classical linguistic education of a bygone era. In striving for inclusivity in the scientific education arena, outdated everyday "non-technical" terminology will either need to be abandoned in the discourse, for example using the term *separate* or *defined* in place of discrete, or treated like a discipline-specific technical term which must be carefully explained by the practitioner. In terms of cognitive load, these propositions are very different: using modern everyday words may lower the processing demands on the students but may result in similar extraneous load caused by cognitive dissonance due to differing connotations of non-technical words for ESL speakers. Whereas introducing new scientific terminology will come with its own high intrinsic load on the working memory, due to its foreignness (Oyoo, 2007, 2017).

Implications for teaching

Scientific language has its fair share of complex technical words like diffract which need to be unpacked for the learner, however, this study corroborates findings of Oyoo (2017) and Cassells & Johnstone (1983) in that non-technical words pose the greatest challenge to scientific understanding. It transpired that by relying on over-simplified non-technical terms such as 'jumps' – whose meaning differs in the minds of ESL students – we may ***create*** difficulties for students. Additionally, the use of outdated non-technical words such as 'discrete' may create further difficulties as these unfamiliar words are not correctly linked in students' mental schema, and as such students are not able to appropriately construct meaning for these terms.

Understanding spectroscopy has foundations in high school topics of fundamental atomic structure, light and the electromagnetic spectrum. Tertiary instructors build on this knowledge between the topics to introduce spectroscopy at university level. It follows that high school teachers and tertiary instructors must speak the same language when teaching students in spectroscopy. To develop their pedagogical science language knowledge teacher/instructor must be aware of the dangers of simplifying language for ESL students and the load the simplified language places on ESL students. In addition to this, a glossary could be drawn up for teachers/instructors and students to use in preparation before beginning work on an abstract and complex topic like spectroscopy. Within the glossary, pertinent technical and non-technical terms should be described in detail.

The pre-laboratory activity, which prepares students to interpret their observations and make inferences, is an ideal place where students can engage with language relevant to the discourse in spectroscopy. In the pre-laboratory activity students could be guided to build meaning for the different terms, for example, an activity to link words with definitions, especially if those definitions are written in accessible language. We also propose providing students with a key or legend which links the terminology to symbols used often in the discourse would provide students with the tools to properly attempt the question, "…***how many emission lines will be seen in the emission spectrum? Show your reasoning using an appropriate diagram***". Such a strategy should allow students greater proficiency in using a specialised language to manoeuvre between the levels of Johnstone's triangle in spectroscopy (Taber, 2013).

In this study we found that students communicate spectroscopic concepts poorest through symbolic representations. This finding has clear curriculum implications: Experts have well developed schema in terms of spectroscopy and can easily navigate the macroscopic, symbolic, and sub-microscopic domains in this complex topic whereas students do not. Re-sequencing the symbolic representations to be the culminating taught component should help impart our expert schema to the students: "The use of sub-microscopic interpretations and the use of representations can be harnessed as ways to bring ideas together, provided that we do not work at too many levels at the same time with novice learners" Reid (2021a, p. 57). In spiralling the curriculum in this way, and starting with the macroscopic, as suggested by Johnstone (1991), we may be able to open doors for learner understanding of invisible mental models. A guided post-laboratory activity, in addition to an individual pre-laboratory activity, may be a solution in this particular context to consolidate understanding.

Conclusion

Language, whether written, spoken or symbolic, is the means through which information and ideas are communicated. It comes as no surprise then, that language proficiency is a requirement for the learning of science. Chemistry with its discipline-specific terminology is an additional language for all students, which must be acquired to achieve mastery, but English as the medium of communication presents additional challenges for ESL learners, especially those without a firm science foundation. In this study we seek to contribute new insights in the challenges posed by technical and non-technical language in the learning of introductory spectroscopy. We uncovered three specific challenges, i.e. that posed by the word family, diffract and refract; the use of the almost obsolete (out-dated) term, discrete; and the cognitive dissonance created by the word jumps rather than drops to describe movement to a lower energy level. While the first of these challenges is anticipated, the other two are new findings not yet reported in the literature. These two potential difficulties are quite simple to address by a teacher that is aware of their presence and mindful of the challenges that ESL learners experience.

Conflicts of interest

There are no conflicts to declare.

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