Addressing barriers to understanding emission spectroscopy for novice chemistry students

by

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Submitted in fulfilment of the requirements for the degree

PhD Science and Mathematics Education

In the Faculty of Natural & Agricultural Sciences

University of Pretoria

Pretoria

2021

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DECLARATION

I, Christine Elizabeth Mundy, declare that the thesis, which I hereby submit for the degree PhD Science and Mathemtics Education at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: ____________________

DATE: 14 July 2021

ABSTRACT

Spectroscopes are practical tools that show the quantization of emitted light from excited elements and compounds, as well as helping students understand modern models of the atom and appreciate the unique identifying power of spectroscopic signatures. Spectroscopic instruments are usually costly and complex, therefore a self-made and low-cost Mini Spec was an ideal way for first-year chemistry students to learn about emission lines and spectroscopy itself.

Design-based research was used over five cycles to devise and refine a laboratory exercise that included the individual construction of a Mini Spec, the use of the Mini Spec to observe discrete and continuous spectra from readily available light sources, and guided interpretation of observations in a report sheet. In the first two cycles the Mini Spec construction time, conceptual multiple-choice items, and student performance were used to gauge barriers to student understanding. In cycles 3, 4 and 5 the data methods changed to gain deeper insights into student sense-making and the associated barriers: students' report sheet explanations were coded according to defined learning outcomes and a recorded collaborative post-lab activity was analysed.

Three primary barriers to students' understanding of spectroscopy emerged over the five cycles: the demands of the task, conceptual difficulties inherent in spectroscopy and language. Cognitive Load Theory was used to interpret and address emerging barriers to student sense-making, and as such, informed all design-decisions made throughout the study. A variety of refinements to the laboratory exercise were implemented over the five cycles, including: providing students with construction templates, guided questions on the components of the Mini Spec, scaffolded reporting of observations, guided questions to help student interpret observational data, and pre- and post-lab activities. In addition, a rubric was developed to evaluate students' levels of understanding.

Refining the laboratory exercise led to a reduction in the demands of the task as evidenced by decreased construction times, improved performance and gains in understanding the components of the Mini Spec. The development of support for the conceptual barriers experienced by students remains an on-going process due to the nature of design-based research, however, progress was made in improving student understanding of spectral line formation and classification. Language appeared to be an underlying barrier that continued to emerge over the five cycles, be it in interpreting Mini Spec construction instructions, the nuances of non-technical terminologies used to describe electron transitions, or the technical terminologies of optics. For example, students interpreted “jumping” as electrons moving upwards only and they struggled to distinguish between refraction, reflection, and diffraction. Students also seemed to avoid unfamiliar and complex words such as discrete and quantized.

Through flagging language as a barrier, this study sought to contribute new insights into novice student difficulties in spectroscopy, over and above addressing known conceptual difficulties. Additionally, the study confirmed the utility of Cognitive Load Theory and design-based research in interpreting and addressing barriers to understanding spectroscopy experienced by novice students.

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CHAPTER 1: Introduction

1.1 Introduction

Spectroscopy is an abstract and complex topic for most first-year students to master, due to its inherent difficulty and the general lack of exposure to spectroscopy over and above what is provided in lectures and textbooks. Basic emission spectroscopy makes the invisible subatomic world of the atom visible to students, creating an exciting, yet authentic, cornerstone on which students and instructors can build models of the atom, theories of bonding and even develop more sophisticated understanding of quantum mechanics. This study seeks to expose first-year students to emission spectroscopy in the laboratory in a manner that will make it accessible without overloading their working memories. The context of the study, an extended programme degree, allows greater scope to build students' understanding over time around complex topics such as spectroscopy. Laboratories in themselves are complex environments and place demands on novice students over and above the conceptual demands of complex topics. Cognitive Load Theory provided the theoretical foundation for this design-based research study, which aimed at identifying and addressing barriers faced by novice chemistry students over several cycles of implementation. The study was designed to improve students' interactions with the appropriate learning outcomes by considering cognitive demands of the spectroscopic tool and the topic itself in a laboratory setting.

1.2 Motivation

I have been working as the chemistry lecturer for the extended programme of the University of Pretoria for several years (see Section 1.3). My research and teaching have lead me to apply and implement the principles of Cognitive Load Theory in the classroom in that I carefully try to pass on my expert scaffolding to my novice students through means such as chunking, worked examples and verbally discussed concept maps. I realised that spectroscopy remained a challenging portion of the first-year extended programme curriculum, despite my efforts with face-to-face teaching, clickers, Peer Instruction, online simulations and dedicated tutorials. Finally, I understood the missing piece of the puzzle: the students lacked the opportunity to interact with the macroscopic components of introductory spectroscopy and emission spectra, and therefore I undertook to introduce a lab exercise to give the students a well-rounded interaction with this topic.

Given the financial constraints, I searched for a tool that would be both educational and low-cost. The Mini Spectroscope (Schwabacher, 1999) stood out from the many homemade spectroscopes, as it appeared the cheapest and easiest to use for novice English second language (ESL) students. It was my intention that by minimising the cognitive load on students in the laboratory, their working memory could be used more effectively for building understanding in such a challenging and abstract topic. However, the introduction of a homemade mini spectroscope into the laboratory was insufficient to realise the gains I had hoped for. This motivated me to reflect deeply on the barriers faced by students in order to refine the design of the laboratory activity.

1.3 Context of the Study

This study was set in an academic development programme at the University of Pretoria. Academic development programmes, in the form extended or augmented programmes, have become prevalent in South Africa to facilitate access to tertiary education for students who would otherwise not qualify for admission by offering holistic development and support (Shay, Wolff, & Clarence-Fincham, 2016). Students on programmes such as these are mainly second language English speakers with limited laboratory experience (Rollnick, Zwane, Staskun, Lotz, & Green, 2001). Such academic development initiatives are designed to promote “access, redress and equity” in the South African context post-Apartheid. The intention is to ensure that incoming students have access as well as a reasonable prospect of success in their chosen field of study (Akoojee & Mokubun, 2007). The focus on student success in these flagship programmes must motivate teaching and learning staff to engage with best practices according to Case, Marshall, and Grayson (2013), to provide students with strong foundations and the true potential for academic career growth.

This study was located in an extended programme for BSc Biological and BSc Physical Sciences students. Further information on the extended programme and context of the study can be found in section 3.5. One of the purposes of the pedagogical structure of the extended programme is the greater depth with which students can interact with topics within the scientific disciplines. The extract below from Shay et al. (2016) describes the intention of the extended or stretched timeline that is integral in this type of academic development programme:

> “The purpose of ‘stretching’ is not simply more time but making the “epistemic architecture” of the various disciplines more explicit. As when stretching fabric where the actual strands, weave and texture become more visible, the extra time is there to make more explicit and more visible the know-that and know-how of the specific disciplines. How this is done is a matter of pedagogy – the selection of material, the assessments that are set, the kinds of learning that are promoted. The assumption of the proposed model is that this ‘explicit making’ pedagogy needs more time.” (pp. 80).

Spectroscopy is one such topic that is included in greater depth in the extended programme chemistry course. In mainstream courses at the University of Pretoria, this topic is often mentioned in a cursory manner but in extended first-year chemistry it is an important topic that is structured to deepen students' knowledge of the evolving model of the structure of the atom. Knowledge of the structure of the atom helps underpin understanding of chemical and physical atomic properties, and theories of bonding and reactivity, which are cornerstone to foundational chemistry. Spectroscopy also highlights the relationship between the quantization of energy and the quantized structure of the atom, allowing extended programme students the opportunity to develop a mature understanding that will be advantageous when students join their mainstream counterparts in their second year.

Prior to this study, emission spectroscopy and atomic spectra were only discussed in lectures and tutorials in the course that I taught. Reasons for the lack of laboratory exposure were the cost of procurement and maintenance of spectroscopic instruments, along with the fact that individual students would have limited access to the instrumentation due to large student numbers enrolled in first-year chemistry on the extended programme. From a pedagogical perspective, students in the past lacked the opportunity to interact with all three faces of the chemistry triplet due to the inaccessibility of the macroscopic component in the form of laboratory work. Furthermore, the lack of laboratory exposure hindered potential meaningful learning in emission spectroscopy which could be achieved through students interactions with affective, cognitive and psychomotor domains (Bretz, 2001; Novak, 1993).

1.4 Spectroscopy and emission lines

Spectroscopy is the study of how light interacts with matter. There are many types of spectroscopy including atomic absorption, atomic emission and fluorescence spectroscopy. Depending on the source and the type of spectra collected, conclusions may be made about the subatomic nature of the atom or about the elemental composition of a certain sample. The principles of emission spectroscopy are traditionally included in first year general chemistry curricula to introduce the notion of quantization and the Bohr atomic model and the basics of quantum mechanics.

Spectroscopes and spectrometers are analytical instruments which are often used to aid teaching and learning of spectroscopy and emission spectra in either the laboratory or classroom. The difference between a spectroscope and a spectrometer is that the former is confined to "visual observation and evaluation" and the latter has detectors for the measurement of radiation (IUPAC Reccomendations, 1995). Since the 1990s international literature abounds with novel spectroscopic tools designed by science educators to help students overcome the "black-box nature" of commercially available spectroscopic instruments (Forbes & Nöthling, 2014; Vanderveen, Martin, & Ooms, 2013).

The simplest form of observing emission spectra would require a diffraction grating and a spectroscopic chart to view real world light sources as described by Jacobs (1997). However, diffraction gratings are costly, especially *en masse*, even with the potential of reusing them annually. Brouwer (1992) used an everyday CD placed behind a gas discharge tube in a darkened room to view spectral lines, however the emission lines did appear curved. A similar approach using a whole CD and real-life light sources is also explained by Finkenthal et al. (1996).

Various homemade spectroscopes were designed to give students exposure to spectroscopy in a real-life context: the CD-ROM Spectroscope was designed by Wakabayashi, Hamada and Sone (1998). Wakabayashi and Hamada (2006) then designed a higher resolution DVD Spectroscope in later years and used digital photographs to capture spectra and aid student understanding. The DVD Spectroscope was further improved into a periscope-type spectroscope that could handle more sophisticated applications (Wakabayashi, 2008). These designs had drawbacks in that they used a whole CD or DVD, were large, complex to make and centred on more complex laboratory procedures. A hand held Mini Spectroscope was designed by Schwabacher (1999) which only used a 16th of a CD, making the emission lines appear authentically parallel. The low cost and portable design were easily adopted and used for a wide variety of age groups. For these reasons, the Mini Spectroscope was chosen as the spectroscopic tool for this study, modified with the permission of Prof Alan Schwabacher, and will be referred to from now on as the **Mini Spec**.

1.5 Statement of the problem

Laboratories are complex learning environments (Rollnick et al., 2001) in which multiple demands are placed on the working memory of the student (Agustian & Seery, 2017; Johnstone & Wham, 1982; Reid & Shah, 2007). Tsaparlis (2009) stated that overload on the working memory is a core problem in laboratory work whether due to multiple stimuli, complex procedures demanding higher order thinking skills or difficulty in linking the macroscopic with the sub-microscopic and symbolic aspects of the activity.

In a complex topic like emission spectroscopy and atomic spectra, the cognitive demands on the students in a laboratory setting will be even greater. Spectroscopy and emission lines are areas where novice students struggle due to the abstract nature of the content and the ease with which misconceptions arise or persist (Burman, 1991; Jones, 1991; Sadler, 1991). Several authors have documented the conceptual difficulties associated with teaching and learning introductory spectroscopy (Körhasan & Wang, 2016; Savall-Alemany, Domènech-Blanco, Guisasola, & Martínez-Torregrosa, 2016; Ivanjek L. , Shaffer, McDermott, Planinic, & Veza, 2015a; Ivanjek L. , Shaffer, Planinić, & McDermott, 2020).

Additionally, there is an abundance of hands-on or student-built spectroscopes to choose from, depending on the level of the students and the outcomes required. Kovarik, Clapis and Romano-Pringle (2020) shrewdly state that very few studies circle back to whether the learning outcomes have indeed been met through the hands-on exercise. It is likely that novice extended programme students who are often academically underprepared or unequalled prepared in different topics due to short-comings at high school, English second language (ESL) students with limited laboratory experience, may encounter more than simply conceptual barriers in trying to master the requisite learning outcomes. This study sought to identify and address these barriers through the inclusion of a well-considered laboratory exercise to promote student understanding in five key pre-defined learning outcomes.

1.6 Rationale

Spectroscopy, emission spectra and quantization are unfamiliar (Burman, 1991) and abstract topics, and are as such difficult for students to grasp (Jones, 1991), often leading to various misconceptions (Sadler, 1991). This was the pedagogical motivation for the introduction of a spectroscopy laboratory exercise which should "provide the macroscopic observations needed for students to connect theory to the physical world" (Vanderveen et al., 2013). In most introductory curricula these topics supplement the understanding of the evolution of the atomic model and prepare the minds' of the students for introductory quantum mechanics (as is the case in this study). However, most first-year students are merely taught spectroscopy in theory; it is not demonstrated nor are students exposed to it in a laboratory setting. There is a variety of reasons for this, including limited time available in the curriculum, the expense and maintenance of spectroscopic instruments and the large student numbers in introductory chemistry courses. The lack of meaningful learning in the laboratory adds to the complexity and challenges to mastery of spectroscopy for all first-year students.

Before the introduction of the Mini Spec laboratory exercise in this study, there was no practical or laboratory component to support the topics of spectroscopy, emission spectra and quantization. This meant that the barriers to learning that students may face in the topic were unidentified and unaddressed. The covert nature of the mind of students meant that identifying instances of sense-making and sense-breaking in this topic required a robust theoretical lens which could provide potential explanations as to what was happening in the minds of the students. Sense-making is the unit of analysis for this study, defined as an improvement in understanding of a particular learning outcome by either a group or an individual student. Sense-making is a cognitive process which is evidenced in this study in written or discursive formats, see section 3.7, 4.1 and 5.1.

Cognitive Load Theory was chosen as a lens to identify barriers as the components of this theory address the availability of working memory (Sweller, 1994). The working memory is a space in the mind where information is held and processed before the possibility of storage in the long-term memory (Johnstone, 1997). If the working memory is flooded or overloaded, meaningful learning will cease to occur and student performance will drop abruptly (Kalyuga, Chandler, & Sweller, 1998; Sweller, Van Merrienboer, & Paas, 1998). Sense-making is an iterative process in the working memory which includes retrieval of prior knowledge from the long-term memory, assimilation and accommodation with new information and the storage of new knowledge in the long-term memory. Observations of breakdown in student sense-making or understanding relating to the learning outcomes of this topic were assumed to be indicative of cognitive overload of the working memory that warrant exploration, as these may represent barriers to students' understanding.

Novice students on the extended programme are typically underprepared for tertiary education and the majority of the cohort is ESL. Both of these factors imply that such students may experience barriers in understanding spectroscopy more acutely: under-preparedness implies student may not have all the necessary prior knowledge and skills required for cognitive processing. In addition, ESL speakers use up to 20 % of the processing power of their available working memory for language related tasks instead of building understanding (Johnstone & Selepeng, 2001).

Inclusive education encompasses a wide spectrum and has fluid meaning dependant on its use; the broad definition of inclusive education practices being the removal of barriers to student participation and learning (Ainscow, 2005; Department of Education, 2001). This study focused on the removal of barriers to create an inclusive laboratory exercise with special attention given to the potential of language emerging as a barrier.

In this study, a laboratory exercise which included the construction and use of a Mini Spec was used to generate basic emission spectra. The Mini Spec was accompanied by a report sheet that guided students in their interpretation of observations. The barriers experienced by students may not be identifiable immediately and additionally, the hypothesised barriers informed by Cognitive Load Theory are not falsifiable. Design-based research was chosen as it represents a powerful methodology that lends validity to this type of emerging education research. The multiple refined iterations to the implementation of the laboratory exercise should generate continually maturing insights of the barriers faced by students with each cycle (see Figure 1).

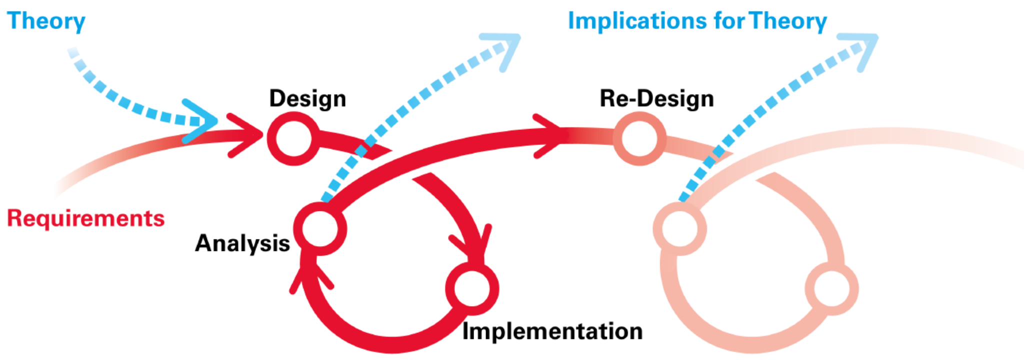


Figure 1.Design-based research as an ongoing process of innovation (Fraefel, 2014, pp. 9)

1.7 Research questions

The aim of this study was to use Design-Based Research, informed by Cognitive Load Theory, to identify and address barriers to understanding spectroscopy for novice university students in a laboratory setting. Therefore, two primary research questions emerged:

1. What were the barriers to understanding emission spectroscopy and how were they identified?
2. How were the barriers to student understanding of emission spectroscopy addressed?

1.8 Contribution of the study

The laboratory is already a complex setting and novice students may lack the knowledge schema to interpret observations or to manoeuvre to higher levels of inquiry in the laboratory (Johnstone & Al-Shuaili, 2001). The researcher contends that an understanding of the cognitive demands on students should allow the identification of different types of barriers faced by students. By addressing these barriers, novice students may transition along the continuum towards appropriate mastery of the learning outcomes for emission spectroscopy, thus enabling students to form appropriate foundations for other interlinked topics in the curricula like quantum mechanics.

This study aimed to make a theoretical contribution to the process of addressing barriers in the laboratory through a design-based research approach informed by a cognitive lens. The researcher contends that not only are the theoretical framework and methodology compatible, but they jointly frame a practical research design to address barriers to understanding and improve student mastery in the novice chemistry laboratory setting.

The refined laboratory exercise represents a tangible contribution to practice that could be introduced into novice laboratory curricula to support spectroscopic understanding. The laboratory exercise along with a pre- and post-lab activity represent learning materials refined to support learning in a complex topic, i.e. a "non-threatening way(s) – in digestible learning quanta, supported by effective scaffolding – and reinforced and applied" (Taber, 2009, pp. 103).

The proposed guiding cognitive pathways that were used to refine the laboratory exercise (see Section 6.3) should distinguish it from either a cookbook type lab, which enables the rote acquisition of lab skills, or an inquiry-based lab, which requires a level of knowledge or schema sophistication that novice students may not have.

1.9 Sequence of the Thesis

This thesis opened in a classical fashion with the introductory chapter, Chapter 1, in which the aims and rationale of the study were made explicit to the reader. In Chapter 2, the relevant literature for this study is discussed, this includes the growth of cognitive learning theories, language issues surrounding learning in science and the theoretical lens of the study. Chapter 3 describes the overarching research design and methodologies used, i.e. design-based research and the use of mixed methods for data collection. Chapter 3 also includes ethical considerations and efforts made to ensure validity of the study.

Chapter 4 and 5 both deal with the findings of this study: Chapter 4 looks at the changes in students' understanding in five distinct learning outcomes over the cycles of the study. Chapter 4 is complemented by a published article required to fulfil the requirements of this thesis (see Appendix A: Mundy & Potgieter, 2020). The article supplements early findings presented in Chapter 4 but also highlights the value that this study had in terms of unsolicited community learning, for both the students and their audience. The findings presented in Chapter 5 only focus on the fifth and final cycle of the study. This chapter gives the reader an indication of the success of the sequential design-decisions and tracks the flow of students' understanding from one learning outcome to the next.

Chapter 6 presents a discussion of the research questions, identifying the barriers to students' understanding of spectroscopy and the extent to which these barriers are addressed. Three primary barriers emerged in the study: the demands of the task, conceptual difficulties and language. Cognitive pathways, drawn from Cognitive Load Theory, are proposed to identify and support the components of the three primary barriers. The concluding remarks, significance of this study and implications for practice, are presented in Chapter 7.

CHAPTER 2: Literature Review

2.1 Introduction

Chapter 2 opens with a brief history of the major learning theories, Behaviourism, Constructivism and Cognitivism, and their contribution to the development of undergraduate chemistry laboratories. Cognitive Load Theory is prominent in cognitive learning theories and provides a versatile design framework for laboratory learning. This chapter includes an investigative meta-analysis of a large body of literature on Cognitive Load Theory, which further illustrates the relevance of this theory to this study. Language and its links to Cognitive Load Theory are pertinent to the students in this study and will be discussed in detail in Section 2.4. Finally, Cognitive Load Theory as the theoretical framework of this study guides both the instructional design of the laboratory experiment and acts as an analytical lens, using the format of cognitive pathways, to address barriers faced by students in emission spectroscopy.

2.2 Laboratory learning and Learning theories

"Learning is a complex process that has generated numerous interpretations and theories of how it is effectively accomplished" (Ertmer & Newby, 1993). Simply, learning theories are theories on how students learn. There has been debate surrounding chemistry laboratories and their role in undergraduate student learning: is it merely procedural for the acquisition of practical and scientific skills, or does laboratory work contribute to the wider process of meaningful learning? These questions prompted review of the three most prominent learning theories: Behaviourism, Constructivism and Cognitivism and the potential they have for informing meaningful laboratory work in this study.

These learning theories are not mutually exclusive, in fact, the simplification and organising of knowledge in Behaviourism resonates with chunking and prior knowledge that are corner stones of Cognitivism. Tenets of Cognitivism have helped support the growth of Constructivism in its many individual and social branches. Even the concept of Stimuli-Response put forward in Behaviourism coincides with the Constructivist notion that new data or experiences may activate an inquiry-based response. However, for the purposes of this literature review the links between the theories will not be expanded upon in depth, the focus will be on the essence of the three major learning theories and their applications in educational contexts, especially the laboratory.

2.2.1 Behaviourism

Ashworth, Brennan, Egan, Hamilton and Sáenz (2004) state that psychology emerged as an independent discipline from the 1850s, which then birthed learning psychology and learning theories, Behaviourism being the first thereof. Behaviourism is rooted strongly in a positivist paradigm, where the responses are measurable. The two pillars of Behaviourism are classical conditioning or Stimulus-Stimulus theory (S-S) (Pavlov, 1987) and instrumental conditioning or Stimulus-Response (S-R) theory (Skinner, 1938). The S-R theory has been used to explain educational contexts in which teachers where seen to control the stimuli and environments that shaped student behaviour (Ashworth et al., 2004).

Behaviourism as a learning theory surpasses basic Pavlovian responses, such as students learning to recognise letters and numbers and learning associated sounds, words and multiplication tables. Behaviourism in the classroom informs the practitioner’s influence by shaping students’ experiences e.g. nurturing a supportive atmosphere to form positive associations for students making presentations to their peers. A Behaviourist lens informing laboratory practicals should facilitate the learning of basic psychomotor skills. Cookbook, traditional or expository laboratories include following procedures, learning experimental techniques, and basic safety responses (Domin, 1999a). Depending on the student, the skills and competencies learnt may elicit satisfaction and confidence in their abilities, however, such a practical design does not allow for growth of scientific thinking and decision-making (Enneking, et al., 2019).

Behaviourism pays no attention to the complex processes within the mind that facilitate reasoning; the dissatisfaction with the superficial nature of Behaviourism led to Neo-Behaviourism, which was the birthing ground for Cognitivism (Tomic, 1993). Many experimental designs or practicals at first-year-level are carried out in an expository manner due to financial constraints, large student numbers and low staff to student ratios (Domin, 1999a; Reid & Shah, 2007). However, the purpose of this study was to uncover barriers students faced in spectroscopy, i.e. the design of the laboratory exercise and the theoretical framework used for analysis must be able to elicit and interrogate students’ higher order scientific thinking. Domin (1999b) found that expository labs focus on lower order skills according to Bloom’s taxonomy (1956) which may leave little time for the higher order thinking required to process the significance of the laboratory experience, therefore a Behaviourist lab design and lens does not suffice in this study.

2.2.2 Constructivism

Cognitivism continued to grow slowly as a theory over the course of the twentieth century, however, Constructivism, came to the fore at the end of the twentieth century attracting a lot of researcher and practitioners attention (Ashworth et al., 2004; Jones & Brader-Araje, 2002). The transition from Behaviourism to Constructivism meant that "knowledge construction is emphasized over knowledge reproduction" (Duffy & Jonassen, 1992; Jonassen, 1994). This learning theory was attractive to practitioners in that the full responsibility for stimulating learning was no longer the sole responsibility of the practitioner: learners and students now take an active role in meaning making or knowledge construction (Jones & Brader-Araje, 2002).

Constructivism, in the context of learning theory, is the belief that people build their own knowledge, and their own representations of knowledge, from their own experiences and thoughts. Constructivism informs educational settings in multiple ways including personal or Individual Constructivism and Social Constructivism. Personal Constructivism (Piaget, 1964; Piaget & Cook, 1952) places the educator at the centre as a facilitator whose objective is to prompt individual action within the student to reform and reorganise schema and knowledge. Social Constructivism (Vygotsky, 1930, 1997) adopts the view that learning is aided by internalisation through social interaction where the educator acts in a mediator role as a more learned individual.

Vygotsky and Piaget both acknowledge the importance of prior knowledge in building new knowledge that underlies all forms of Constructivism: be it in processes of assimilation, accommodation or activating the zone of proximal development with the help of a more knowledgeable other. Implications of a Constructivist approach for practitioners is that students' current knowledge and background must be considered in teaching and learning. This is particularly relevant for any teaching in scientific fields since students already have a preconceived notion of how the world works based on observation of their own natural environment, cultural upbringing and the developing schemas used to explain their observations (Jones, Carter, & Rua, 2000). If not managed appropriately the knowledge that students bring with them into the classroom, i.e. their preconceptions, often form the basis of alternate conceptions or misconceptions as they may be "not in harmony with the science views or are even in stark contrast to them" (Duit & Treagust, 2003). These alternate conceptions are very durable and will only be altered once the students undergo conceptual change at a personal level: they must become dissatisfied with their own current concept in favour of a new concept which must be intelligible, plausible and fruitful (Hewson, 1982).

Be this as it may, Constructivism has left a legacy in educational practice in the understanding and interpretation of knowledge production has shifted from a passive to an active process in the mind of the learner (Jones & Brader-Araje, 2002). Constructivist principles continue to guide many educational initiatives in scientific disciplines as it closely corresponds to the nature of science, including inquiry based laboratories (Buck, Bretz, & Towns, 2008) and learning approaches such as Process Oriented

Guided-Inquiry Learning (Moog, 2014). Novak's theory of Human Constructivism in particular is useful in guiding teaching and learning in chemistry education and research (Bretz, 2001). Novak proposes that meaningful student learning must encompass three domains: cognitive (thinking), psychomotor (doing) and affective (feeling) (Novak, 1993, 1998, 2010). Galloway and Bretz (2015) developed the Meaningful Learning in the Laboratory Inventory (MLLI) to assess the three domains of the laboratory experience for undergraduate chemistry students. However, findings from at least two studies suggested that that students' expectations of cognitive and affective experiences were not often met (Bretz, Galloway, Orzel, & Gross, 2016; Galloway & Bretz, 2015).

2.2.3 Cognitivism

Cognitivism began a slow germination parallel to, or in fact slightly prior to, Constructivism (Ashworth et al., 2004). Cognitivism focuses on internal learning in the human mind, that is the processing and storing of information (Ertmer & Newby, 1993). Cognitive Load Theory is a prominent cognitivist learning theory that focuses on two basic memory components, the working memory and the long-term memory, and the interplay between the two (Sweller et al., 1998; Reid, 2009).

The Information Processing Model serves as a blueprint for understanding the tenets of Cognitive Load Theory. The Information Processing Model was brought to the attention of the science education community by Johnstone (1991, 1997, 2006, 2010). This model builds on patterns of human thinking that are proposed to be universal (Ausubel, 1968; Piaget, 1964). The model includes both external stimuli and the elements that the individual brings with them into a learning situation, that is, the model considers processing from both the top-down and the bottom-up (see Figure 2). Johnstone's Information Processing Model has had profound implications on many instructional designs and teaching practices in science education and has been used to explain various research findings (St Clair-Thompson, Overton, & Botton, 2010).

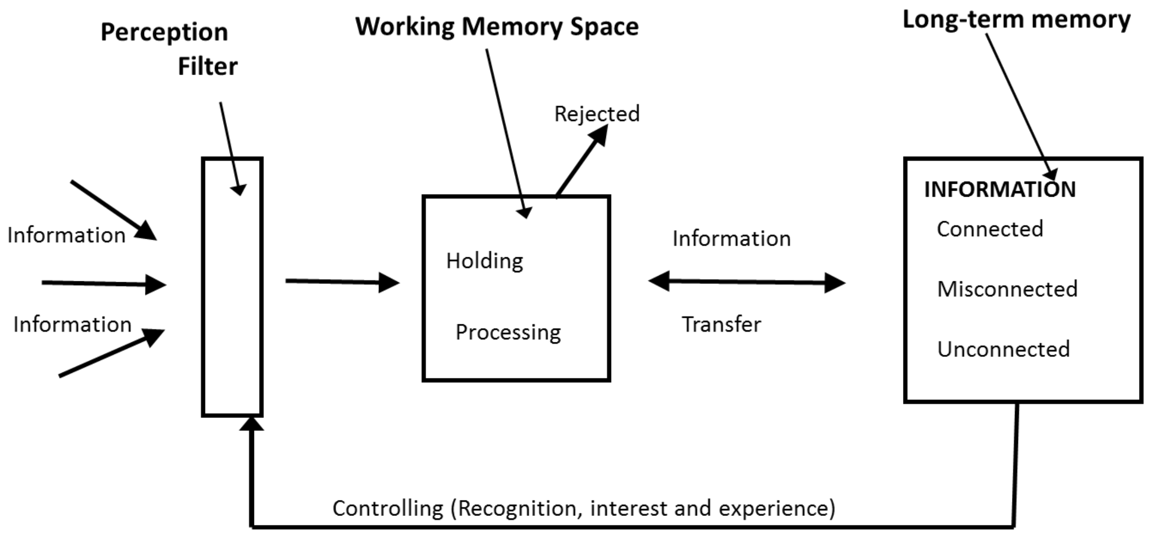


Figure 2. Information Processing Model taken from Johnstone (2006, Fig. 4)

Figure 2 is based on the work of Johnstone in which incoming information or external stimuli reach the mind of the student in the form events, observations, and instructions. All incoming information must first interact with the perception filter before passing through to the working memory. The perception filter is unique and personal; a space in the mind where the knowledge, interests and beliefs that are stored in the long-term memory come to the forefront to help the student select relevant information from the information presented. Not all of the information may pass through to the working memory intact; some information may even be rejected at this stage if it does not make sense. The working memory is a limited space in the mind in which information is stored and processed, in fact, there is a trade-off between how much can be temporarily stored and how much information can be processed at any given time. It is in the working memory that students attempt sense-making through an iterative process of retrieval and storage of knowledge in the long-term memory. The knowledge already stored in the long-term memory is often referred to as prior knowledge. If prior knowledge was processed then stored correctly, it forms part of growing functioning mental schema; if not, the knowledge may remain disparate or incorrectly linked, making it difficult for students to retrieve or build upon.

Johnstone (2010) points out overlap between components of the Information Processing Model, namely, the Ausubelian (1968) notion that new information needs to be linked in a meaningful way to prior knowledge, experience and beliefs; is accounted for by the mechanism proposed between the long-term memory and the perception filter in the Information Processing Model. Furthermore, Johnstone (2010) explains the links between the working memory and the Piagetian (1964) notions of the active processes happening in the mind, such as conflict and dissonance or assimilation and accommodation.

In attempting to address the barriers students are faced with in emission spectroscopy, the factors that hinder the mechanisms of the working memory are of extreme importance, so too are other cognitive components that may improve the capability of the working memory. Cognitive Load Theory was suitable for this study as it describes the factors that influence the availability of working memory and its interplay with the long-term memory (Sweller, 1994; Sweller et al., 1998). It is important to note that the Information Processing Model is a simplified offering by Johnstone for the scientific community to improve teaching and learning whereas Cognitive Load Theory stands as a principle of cognitivism that is not discipline specific.

Sweller (1994) proposed that cognitive load has at least two additive components, the intrinsic load and the extraneous load. The intrinsic load is unique to the learning materials and the elemental interactivity, in other words, the intrinsic load is specific to the topic at hand: for example, its unfamiliarity, inherent complexity and difficulty. Initially intrinsic load was considered fixed regardless of instructional manipulations (Paas, Renkl, & Sweller, 2003), however, in more recent literature it has been acknowledged that the instructor can choose the complexity of the topic to fit the level of expertise of the students, hence managing the intrinsic load with sequencing and selection to limit elemental interactivity (De Bruin & Van Merriënboer, 2017; Van Merriënboer, Kester, & Paas, 2006). However, Van Merrienboer and Sweller (2005) state that inevitably students at some stage must face the full intrinsic load of the topic at hand.

The extraneous cognitive load or ineffective cognitive load hinders schema acquisition and automation (Paas et al., 2003). Extraneous cognitive load is viewed as artificial because it arises from the instructional methods and materials (Sweller, 1994). Seery (2012, pp. 25) explains that “poor materials or those that require a large amount of working memory to process will increase the (cognitive) load and leave little capacity for learning”.

In later literature, a third component of cognitive load was proposed: Paas et al. (2003) refer to germane load as being effective as it increases the extent of learning. Germane load represents the cognitive processes enabling the acquisition and automation of schema or linked chunks of information; this is particularly important for problem solving. Germane load can also be seen as the mental effort required for learning (Van Merrienboer & Sweller, 2005) or load caused by genuine learning processes (Van Merriënboer et al., 2006). Seery (2012) further explains that the extent of processing ability remaining for germane load represents the remainder after intrinsic and extraneous load have been taken into account. However, there is debate around whether germane load represents a third type of cognitive load, as it is so closely linked to intrinsic load and is therefore, difficult to measure directly (Kalyuga, 2011). Some later studies have omitted the construct (Kirschner, Sweller, Kirschner, & Zambrano, 2018), however, the larger body of literature on Cognitive Load Theory has not dispensed with germane load as an additive load to date.

Cognitive Load Theory has implications on how instruction and instructional materials are designed: "Learning will be difficult if cognitive load is high, irrespective of its source" (Sweller, 1994, pp. 308). If cognitive load is too high, meaningful learning ceases to occur, and student performance may collapse (Reid, 2008; Johnstone & El-Banna, 1989). However, cognitive load can be manipulated through reducing extraneous load, carefully selecting the intrinsic load and either allowing mental capacity for processing or scaffolding the intended processing (germane load) (Sweller, 2006).

Cognitive Load Theory was initially criticized for omitting the social nature of learning, but this theory has expanded in recent years to include notions of social agency in multimedia learning (Mayer, 2014, 2017; Moreno, Mayer, Spires, & Lester, 2001) and collaborative cognitive load in group environments (Kirschner, Paas, & Kirschner, 2011; Kirschner et al., 2018). The Cognitive Theory of Multimedia Learning considers the working memory in the context of cognitive load and dual coding (Mayer, 2014). Mayer's (2014, 2017) model is explicit in that learning is **active** (in the retrieval from the long-term memory and the processing in the working memory), **dual-channel** (information can be presented either visually or audibly and held for a very limited time in the sensory memory before selection into the working memory), and finally the working memory is indeed of **limited capacity** (see Figure 3).

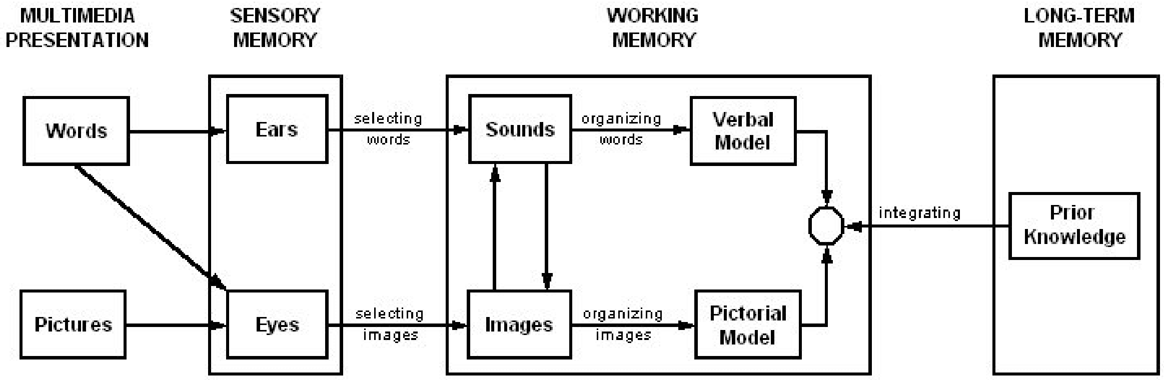


Figure 3. Information Processing Model (Mayer, Heiser and Lonn, 2001, Figure 2, pp. 190)

A significant criticism of Cognitive Load Theory is that it is unfalsifiable i.e. not directly measurable and as such, it is not a truly objective theory (Gerjets, Scheiter, & Cierniak, 2009; Martin, 2017). In his extensive review De Jong (2010) also acknowledges this issue and brings up other concerns with

Cognitive Load Theory, including the entanglement of the types of load and whether the three types of load can simply be added to represent total processing occurring in the working memory. However, Gerjets et al. (2009) give a balanced view on the criticism of the lack falsifiability by drawing on the work of Sneed's structuralist views of theories to counteract Popper's critical rationalism, "a theory has scientific value if it can explain and predict empirical findings, even if its assumptions are not testable". Gerjets et al. (2009) encourages the use of the components of cognitive load as axioms that can be used to structure instructional design and add to further theory, instead of being theory in and of themselves.

After an extensive review of pre-lab activities, Cognitive Load Theory has been recommended as a versatile framework to structure pre-lab design, regardless of the format of the pre-lab activity e.g. video, discussion, or simulation (Agustian & Seery, 2017). It is acknowledged by Winberg and Berg (2007) that the simultaneous acquisition of practical skills, the use of complex equipment along with attempts to build theoretical understanding are all potential sources of cognitive load in the laboratory. In their research, a pre-lab exercise in the format of a virtual simulation resulted in students having more cognitive captivity to ask theoretical questions during the practical, whereas the control group asked more procedural questions. Winberg and Berg (2007) proposed that the simulation allowed students to build functioning schema which lowered cognitive load during the laboratory task. Scharfenberg and Bogner (2010) used a different format: a short group discussion was added to the end of an existing pre-lab that contained both practical and theoretical information. The instructor, who prompted the students to think about their hypotheses and expected results before beginning the experiment, guided this discussion. Students who underwent this two-step pre-lab activity exerted less mental effort in interpreting their actual practical results and showed greater long-term cognitive performance.

In circling back to meaningful learning in the laboratory, Schmidt-McCormack, Muniz, Keuter, Shaw and Cole (2017) designed sets of three videos: a pre-lab, an experimental, and a data analysis video. Cognitive Load Theory and the Cognitive Theory of Multimedia Learning featured prominently in the design of these videos. The authors used the Meaningful Learning in the Laboratory Inventory (MLLI) to assess the students' experiences and found a positive shift in the students' perception of their experience in the affective domain, which is unlike the findings of Bretz and co-workers (Bretz et al., 2016; Galloway & Bretz, 2015). Schmidt-McCormack et al. (2017) attributed the confidence and autonomy experienced by students to the carefully designed resources informed by cognitive load.

Cognitive Load Theory was chosen as the lens for this study as it shares many principle constructs from early theorists in the education fields. It also does not seek to replace expository or inquiry based labs, and the learning theories that inform them: Cognitive Load Theory can be utilised as an overarching framework to pinpoint areas of breakdown along with add guidance for appropriate scaffolding throughout the laboratory experience, including the pre- and post-lab activities (Reid & Shah, 2007). In the next section, the rise in popularity of Cognitive Load Theory in educational research gives further credence to the suitability of Cognitive Load Theory as the theoretical lens in this study.

2.3 Meta-analysis of Cognitive Load Theory

> "Cognitive load theory has undergone continuous development over the last three decades. The driver of that development has had two major sources: the generation of new data based on randomised, controlled trials that have suggested additions and modifications to the theory, and the incorporation of external theoretical constructs that resonate with the theory. Both sources of theory development have been critically important to the success of the theory." (Sweller & Paas, 2017, pp. 85)

In this meta-analysis, this statement is explored by mapping the frequency of Cognitive Load Theory publications back to the year 1900. Alongside this, the frequency of publications on Constructivism is mapped, as it remains the dominant learning theory, especially in the sciences. The second part of the meta-analysis sought to explore trends and developments in Cognitive Load Theory based on a sample of abstracts from the first six months of 2018 which was the year was when the literature review was first drafted. The full methodology of this meta-analysis can be found in Appendix B.

In Figure 4 the frequency of educational publications grounded in Constructivism can be seen in blue. The popularity of this learning theory grew rapidly from the 1990s but appears to have peaked in 2012 and has begun to taper off. The gross number of Constructivist educational publications from 1900 to 2020 dwarfs the number of educational publications dealing with Cognitive Load Theory (see orange) by a factor of 6. However, there is a marked increase in interest in Cognitive Load Theory educational publications in recent decades, which shows no indication of tapering off or peaking. The momentum behind research in Cognitive Load Theory allowed it to surpass Constructivism in 2020.

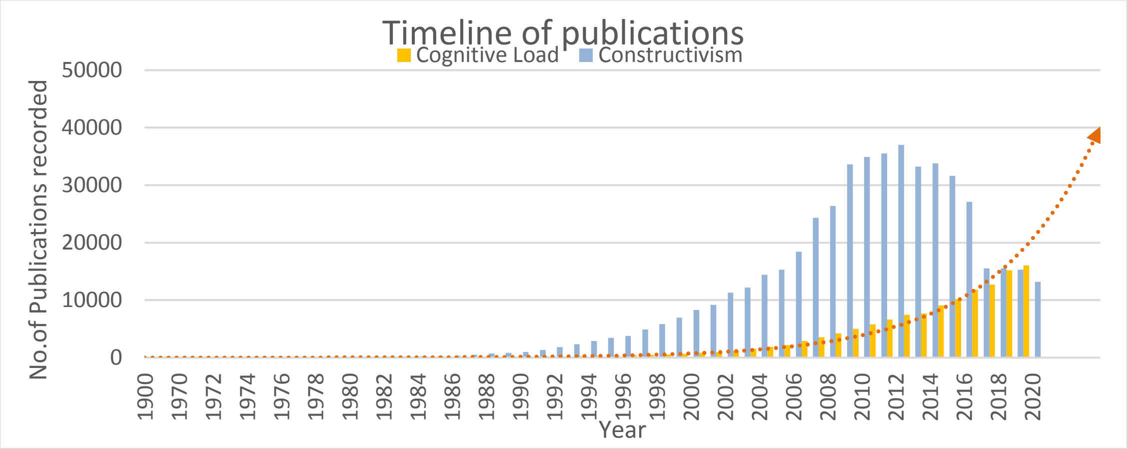


Figure 4. Trends in the frequency of educational publications in Constructivism and Cognitive Load Theory with time (1900-2020)

The second leg of the meta-analysis revealed research directions and emergent themes in Cognitive Load Theory studies. The 42 abstracts that met the requirements were analysed to evaluate the instructional level of the studies, the disciplinary context of the studies and finally the focus areas. There is strong application of Cognitive Load Theory in tertiary education (university, college etc.), more than twice as large as the combination of instances in elementary (kindergarten to the end of primary school), and secondary (high school) instruction combined (see Figure 5).

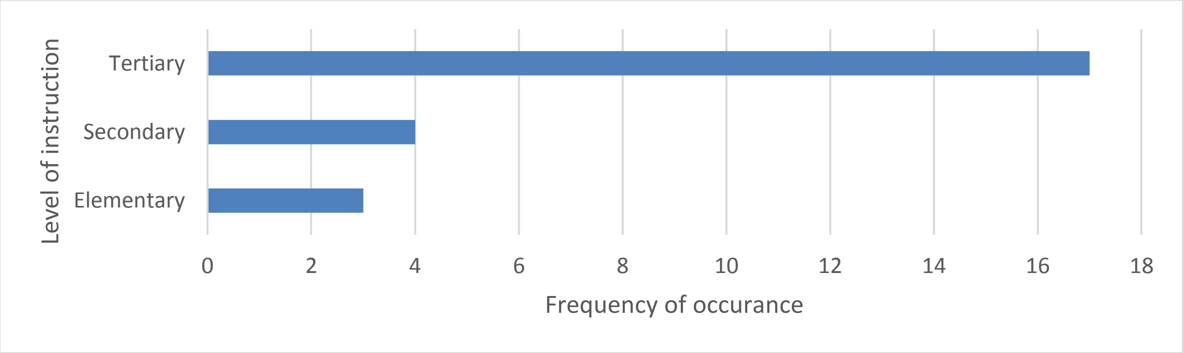


Figure 5. Frequency of educational publications using Cognitive Load Theory at different levels of instruction

The disciplinary context of the studies was divided into five broad groupings (see Figure 6). Social science education included language studies and geography, and, medical education included the training of health care professionals in various medical disciplines. Interestingly, medical education is the forerunner in using cognitive load in instructional design e.g. virtual cadaveric dissection training (Andersen, Konge, & Sørensen, 2018), ultrasound simulator performance (Aldekhyl, Cavalcanti, & Naismith, 2018) and surgical skills training (Dias, Ngo-Howard, Boskovski, Zenati, & Yule, 2018).

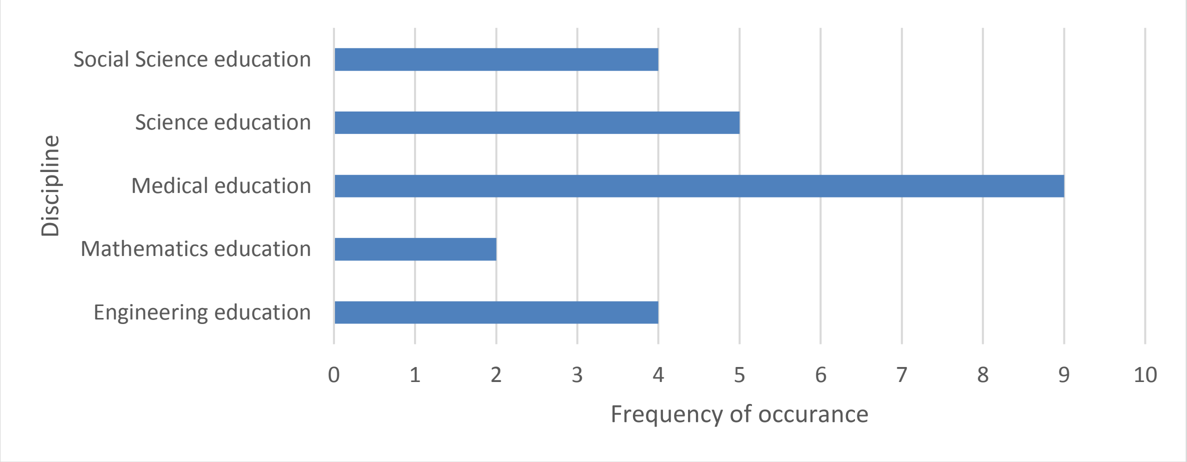


Figure 6. Frequency of educational publications using Cognitive Load Theory per educational discipline

In the final analysis of the 42 abstracts, the current focus areas of Cognitive Load Theory in educational research are explored. Four codes emerged from the abstracts, where more than one code may have been assigned per abstract depending on content. Where abstract content was unclear, the full texts were evaluated before assigning codes to sections of the abstracts. The four final codes are defined as follows:

1. **Cognitive Load Theory and technology:** where Cognitive Load Theory informs the choice of technology, type of technology, type of software and interface design.
2. **Contributing to the theory**: Adding to the understanding of Cognitive Load Theory or looking at Cognitive Load Theory in conjunction with, or in comparison to, other psychological or educational theories.
3. **Improving pedagogy:** using Cognitive Load Theory to cater for students' needs by instructional design and directly manipulating the variables of Cognitive Load Theory to achieve greater student success (which were not always effective).
4. **Measuring Cognitive Load in the educational environment**: via theoretical constructs, written tests or via technology like eye-tracking and neural networking.

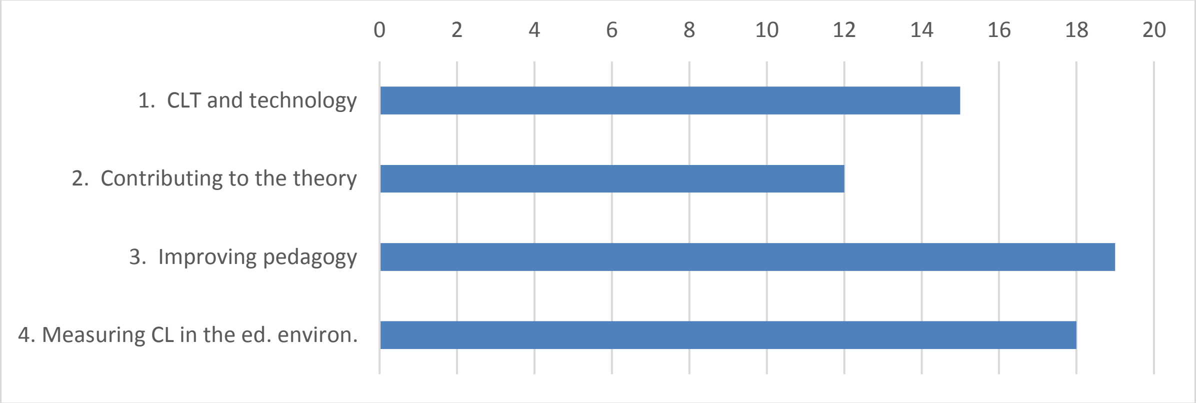


Figure 7. Emergent codes indicating current focus areas in Cognitive Load Theory, CLT

The four focus areas were fairly evenly distributed in the abstracts available (see Figure 7); this finding builds on the applications and focuses of Cognitive Load Theory reviewed by Ayres & Paas (2009).

In summary, this meta-analysis suggests that Cognitive Load Theory is gaining momentum, especially in the tertiary context, which aligns with the context of this study. The frequency of this theory in guiding studies in the medical sciences testifies to the usefulness of Cognitive Load Theory, whether it is unfalsifiable or not. There are overlaps with two of the four focus areas: this study aims to improve pedagogy in the spectroscopy laboratory (code 3). Secondly, the lens of Cognitive Load Theory should contribute a theoretical understanding of language as a potential barrier for the students in this study (code 2). Language and Cognitive Load Theory are further discussed in the next section. Additionally, we contest that the combination of Cognitive Load Theory and design-based research will make theoretical contributions to the methodology of evaluating barriers to laboratory learning.

2.4 Language and Cognitive Load

Tomic (1993) criticises the Behaviourist view of language acquisition, as a simplistic viewpoint that only covers the foundations of language, not the development of complex meaning of words linked to pre-existing knowledge or relevant scientific schema. However, since the inception of cognitivist learning theories, there has been a branch focusing on students' language abilities in terms of optimal assimilation and comprehension (Carrell & Eisterhold, 1983). Coady (1979) put forward an English as a Second Language or ESL Schema theory and ESL reading pedagogy model which encapsulated linguistic schema theory at the time: an interconnected model with three tenets: conceptual abilities, processing strategies and background knowledge. In hindsight, it can be seen how such a model is very similar to the Information Processing Model that we now know (Johnstone, 1997). Background knowledge featured strongly in linguistic schema theory in terms of the existing knowledge students are *assumed* to bring with them versus the individual and cultural background knowledge that they *actually* bring with them (Carrell & Eisterhold, 1983). This delicate interplay fits with the more modern notions of prior knowledge stored in the long-term memory and the influence that stored knowledge and experiences have on the individual's perception filter.

Rollnick (2000) noted that both Social Constructivist theories and cognitive theories have had strong influences in understanding language acquisition. That is, language develops socially, but that most of the processing is individual. In terms of scientific language, Seah and Silver (2020) expand 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, Markic, & Ryan, 2015). There are various terms to describe the groupings of students and their exposure to English as the medium of instruction: English as a second language (ESL or L2), English as a foreign language (EFL), English as an additional language (EAL) and the most recent South African addition, Language of learning and teaching (LOLT), to mention but a few. 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 we know that more than 80% of the student cohort in general does not speak English as their home language even though they are proficient in its everyday language use.

Regardless of the acronym used, learning science as an ESL student presents additional challenges: students may not have automatic access to the meaning of word or extensive scientific vocabularies, and as such may have to rely on context to infer meaning (Mayer, Lee, & Peebles, 2014). The construction of meaning creates additional cognitive load, which may overload the capacity of students who are most vulnerable e.g. lower performing students (Fung & Yip, 2014, pp. 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, but may be transient in the minds of the students as they are not able to assimilate the vocabulary into their long-term memory (Johnstone & Selepeng, 2001; Rosebery, Warren, & Conant, 1992).

Whether students are ESL or first language speakers, proficiency in English is the key to conceptual proficiency in science (Prinsloo, Rogers, & Harvey, 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 e.g. electricity and water (Prinsloo et al., 2018). These findings relate to earlier findings by Cassels and Johnstone (1984) that the complexity of language placed an unwelcome cognitive load on the students which impacts on students' performance in multiple-choice items. Interestingly, all the students in the sample studied by Cassels and Johnstone were considered first language English speakers. However, the processing of language places particularly large demands on the working memory of ESL students (Johnstone & Selepeng, 2001). Kelly (2010, pp. 5) outlines some of the stages of processing that ESL students face in chemistry: "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".

Rees, Kind and Newton (2018a) argue that all students are non-native speakers of chemistry, i.e. 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 barriers to novices who need to be able to link the macroscopic, sub-microscopic and symbolic levels of chemistry concepts (Taber, 2009). Rees et al. (2018a) elaborate on this point:

> "During chemistry learning, novice students must move between these three levels, often without notice or explanation. This introduces significant complexity for novice chemists. Each level has its own characteristic language, and a successful learner develops competence in and confidently inter-relates these three aspects." pp.4.

However, in order to be conversant in the language of science and to build understanding of scientific concepts, a general language proficiency is required. In the words of Childs et al. (2015, pp. 421) "There can be no teaching, learning, thinking, or understanding in any subject without a basic proficiency in language". Rollnick (2000) confirms that many South African students entering higher education possess general proficiency in the English language, however, Oyoo (2007) states that even though students may have a general proficiency, language difficulties arise when terms are used in a scientific context and their meaning changes. In this literature view, we focus on the two main types of language terminology used in the scientific or chemistry classroom: technical and non-technical terminology as first described by Gardner (1972) expanded on by Oyoo (2007, 2017) and revisited in more detail by Quílez (2019). 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* where possible.

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) 1. **Discipline specific** *e.g. photon* 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. 2. **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). 3. **Symbolic language** *e.g.* e^{-}, λ, H Chemists use a specific symbolic language to explain the links between macroscopic observations and sub-microscopic representations (Rees, Kind, & Newton, 2019; Taber, 2009)	Defined broadly as everyday words that take on a scientific meaning when used in scientific disciplines. Non-technical terminology also includes meta-representational terms i.e. commands such as explain or discuss, and, logical connectives such as since, therefore and thus (Oyoo, 2007). However, commands and connectives are not of interest in this study. Of interest is the following: 1. **Non-technical terminology in scientific contexts** *e.g. excited, reflection* 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). 2. **Teleological terminology** *e.g. share, jump* The use of simplified terms that result in personification, animism or anthropomorphism in an attempt to improve student understanding (Taber & Watts, 1996; Quílez, 2019)

Oyoo (2007) argues that technical terminologies are foreign to all students, regardless of whether the students are first or ESL speakers due to the fact that the scientific meaning of a word is different from its everyday meaning. Childs et al. (2015) highlight words with dual meanings in either the non-technical or technical vernacular as problematic. For example, the word reflection in everyday use has at least two very different meanings: it can refer to the mirror image or mean contemplation. In chemistry and physics, reflection means a change in direction of an object or force. It is often difficult to discern whether a word is technical or non-technical in its origins as language and science have evolved alongside, however, if words do indeed have dual meanings this create more difficulties than discipline specific words that have no bearing on everyday speech.

Students face difficulties with technical terminologies when they have not fully grasped the concepts the terms represent; this often leads to students interchanging similar looking or sounding words without full understanding of the difference in their meaning (Rees, Kind & Newton, 2018b). Interchanging of words or incorrect technical word choices can also arise from confusion associated with words in the same word families. Additionally, Rees et al. (2018b) note that students often lack the ability to link scientific words to more common words used in the classroom i.e. the students choose to copy the everyday words used by the instructor, instead of selecting more scientific words with more appropriate meaning. This finding may indicate a lack of properly interconnected schema relating different word choices to the same scientific concepts.

In summary, the link between Cognitivism and language was presented along with the impact language proficiency has on students' performance and ability to participate in scientific discourse. The root of language difficulties lies in the meaning-making associated with technical and non-technical terminology which the researcher has attempted to outline. In closing, the statement by Childs et al. (2015, pp. 441) resonates with this study, "The barrier presented by language is worse because it is largely unrecognisable". There are strategies to overcome this mentioned in the literature, first and foremost practitioners need to be aware that language will place demands on students. Oyoo (2007, 2017) is concerned by difficulties of everyday words used in the science context, encouraging teachers to explain both technical and non-technical terminology to students. Posel and Grapsa (2017) advocate for more quality time to be spent engaging with scientific discourse both inside and outside of the classroom. A final quotation below from Rosebery et al. (1992) reaffirms the cognitive pressure placed on students by language but also advocates for the promotion of social learning whereby the responsibility for acquiring meaning making is shared:

> "Cognitively, students share the responsibility for thinking and doing, distributing their intellectual activity so that the burden of managing the whole process does not fall to any one individual. The sharing of intellectual responsibility is particularly effective for language minority students because the English language demands of complex tasks… can overwhelm and even mask their true abilities and understanding". pp. 63-64

2.5 Theoretical Framework applied in this Research

Rollnick et al. (2001) highlight the complexity of laboratories for first year students at South African institutions, as many students lack communicative competencies required to synthesize arguments in their laboratory write-ups. Laboratories are complex environments, as there are multiple demands on the students, however, the Information Processing Model was successfully applied by Johnstone, Sleet and Vianna (1994) to create an effective laboratory course that improved students attitudes. In a large-scale review by Agustian and Seery (2017) the complexity of the laboratory environment was highlighted again and cognitive scaffolding in the form of pre-lab activities were recommended based on Cognitive Load Theory to improve student processing in the laboratory. The successful incorporation of Cognitive Load Theory into laboratory environments adds to the motivations for a cognitive load theoretical lens in this study (Scharfenberg & Bogner, 2010; Schmidt-McCormack et al., 2017; Winberg & Berg, 2007).

The theoretical framework of this study aligns with Novak's (1993) Human Constructivism in the laboratory environment, in which the teacher and the learner create meaningful learning together by engaging with the cognitive, affective and psychomotor domains i.e. thinking, feeling and doing are all required (Bretz, 2001). In terms of Cognitive Load Theory, affective experiences or feelings are influenced by stored experiences in the long-term memory: the long-term memory informs the perception filter and as such enhances student interest in the laboratory. Additionally, the working memory is the place where not only cognitive processing occurs but also where thoughts, ideas and beliefs are first formed before passed through to the long-term memory (Reid, 2009). Logically an interface also exists between psychomotor experiences and the working/long-term memory in the ability with which students store and build on laboratory skills. For example, basic titration skills are used as the backbone for more advanced titration procedures, or in the case of this study, the use of a Mini Spec and an understanding of its components should develop very simplistic, but nevertheless very tangible prior procedural knowledge for using more complex spectroscopic equipment.

Moreover, this study selected Cognitive Load Theory as lens for additional reasons, firstly such a lens has already proven useful in supporting students learning on the extended programme (Mundy & Potgieter, 2019). Secondly, the findings of the meta-analysis show Cognitive Load Theory is current and growing in popularity especially in the tertiary education sector. Finally, cognitive theories can be modified and may accommodate new theory (Sweller & Paas, 2017). This flexibility in the theory should allow for grounded speculation, and even the growth of theory, encompassing language as a barrier. The ability of Cognitive Load Theory to expand and incorporate other theories is key to the feedback loop of 'theory informing practice' and 'practice informing theory' that is inherent to design-based research, which was the chosen research design for this study and will be discussed in Chapter 3.

The theoretical framework of this study is outlined diagrammatically in Figure 8. As said previously, Cognitive Load Theory is based on the interplay between the working memory with its finite capacity and the long-term memory, for these reasons the researcher has chosen to embed the components of Cognitive Load Theory (extraneous, intrinsic and germane) in the working memory component of Johnstone's (1991, 1997, 2006, 2010) Information Processing Model. Dual channels of incoming information were found to be particularly relevant to reducing cognitive load on ESL students (Mayer et al., 2014). As language barriers are of primary concern in this study, the diagrammatic model of the theoretical framework includes the **visual** and **auditory** channels of Mayer's Information Processing Model of Multimedia Learning. The sensory memory, where images and sounds are held for a moment in time includes the perception filter in Figure 8, as the perception filter will select the format of information before it passes to the working memory. In essence, this figure represents the theoretical framework of this study by enumerating all the components that influence cognitive load on the students. In Chapter 6, cognitive pathways that emerge from this theoretical framework will be analysed to inform the discussion for the findings.

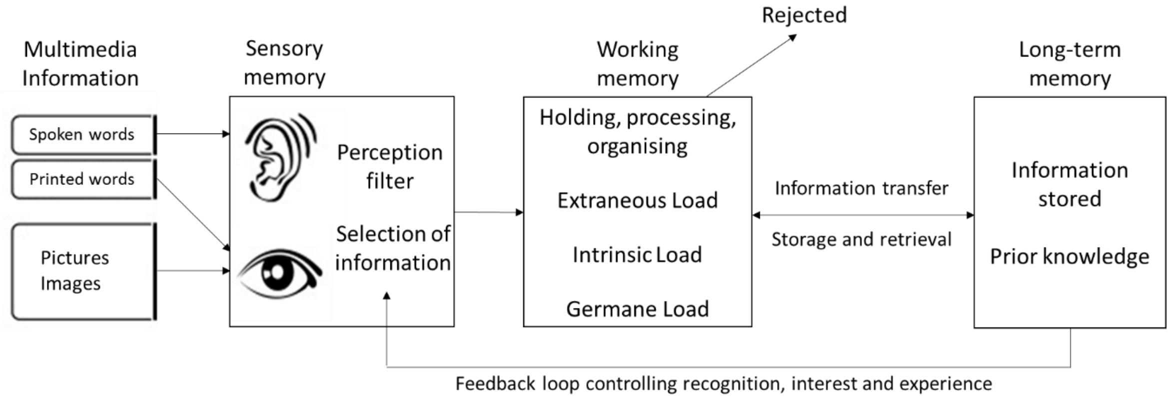


Figure 8. Diagrammatic representation of the theoretical framework of the study

2.6 Summary

In this literature review, three of the most prominent learning theories were explored, i.e. Behaviourism, Constructivism and Cognitivism. The tenets of learning theories had to be understood before the researcher could examine their contribution to the evolution of undergraduate chemistry laboratories. It was found that Cognitive Load Theory can be used in tandem with laboratory environments to enrich student experiences either traditional or inquiry-based laboratories. Cognitive

Load Theory was chosen for this study due to its growing popularity and use in tertiary research contexts, especially scientific and medical disciplines. Cognitive Load Theory also helped the researcher understand the basic cognitive demands of language acquisition and the increased demands of scientific language discourse for students, especially those who are English second language speakers. Chemistry in particular presents challenges as technical and non-technical language are used to navigate the levels of the chemistry triplet. In closing, the diagrammatic representation of the framework chosen for this study included the Information Processing Model and elements of the Cognitive Theory of Multimedia Learning.

CHAPTER 3: Research Design and Methodology

3.1 Introduction

In this chapter, the researcher explains the methodological journey taken to identify and address barriers to student understanding in emission spectroscopy. The researcher's position and paradigm are presented both of which informed the research design and methodological approach. The context and the nature of the study are strongly intertwined given the nature of design-based research. The analysis section is atypical for a thesis, as brief reflections and findings needed to be incorporated in line with the principles of design-based research. This chapter closes with quality standards pertinent to the study along with ethical considerations and limitations.

3.2 Position of the Researcher

First, and foremost, in the mind of the researcher is a respect for the mind of the student and the cognitive load that the introduction of any new laboratory experiment may produce. The researcher is also the practitioner, or lecturer, in this study; from the practitioner's perspective Cognitive Load Theory will inform attempts to mitigate factors that encroach on the processing capabilities of the students' working memory. From the researcher's perspective, Cognitive Load Theory feeds naturally into design-based research; therefore, this combination should progressively reveal the reality of the barriers that students face in studying emission spectroscopy. The pursuit of knowledge in this study aims to be both scholarly and practical. However, to achieve these ends the researcher must embrace both patience and reflection along the cyclic journey of design-based research. As both practitioner and researcher, I am aware of the characteristics of novice students entering tertiary education in the pursuit of a qualification in the STEM fields. Such students are often under-prepared and easily overloaded; therefore, I strongly believe that there is a place for cognitivist design-based research in the educational toolbox of well-rounded researchers and practitioners who deal with first-year students.

3.3 Research Paradigm

Morgan (2007, pp. 50) defines paradigms as "shared belief systems that influence the kinds of knowledge researchers seek and how they interpret the evidence they collect". For example, positivists and post-positivists are concerned with the ultimate, objective and measurable truth of a situation, which corresponds to a quantitative methodology (Mackenzie & Knipe, 2006; Teddlie & Tashakkori, 2009). Constructivism and interpretivist paradigms correlate largely with qualitative research methods, in which the socially constructed view of the world creates meaning. Pragmatism, on the other hand, joins the two seemingly incongruent paradigms, or paradigms at war, to create a view that seeks a methodology in which the researcher can interpret the results.

In terms of the pragmatic paradigm, the research question is central to the study, and the methodological approach must serve this. Johnson and Onwuegbuzie (2004) see pragmatism as the desire to create a workable solution from the joint insights of qualitative and quantitative research. Furthermore, pragmatic research is considered a practical and outcome-oriented method of inquiry as it allows the mixture of the best methods to answer the research questions (Johnson & Onwuegbuzie, 2004).

The researcher adopted the pragmatic paradigm as it also places high regard on the inner world of learning whilst at the same time "recognizes the existence and importance of the natural or physical world as well as the emergent social and psychological world that includes language, culture, human institutions, and subjective thoughts" (Johnson & Onwuegbuzie, 2004, pp. 18).

Pragmatism is such a useful paradigm, thus Onwuegbuzie and Leech (2005) recommend that adherence to old dualistic paradigms be abandoned in favour of embracing both under the umbrella of pragmatism. Onwuegbuzie and Leech (2005) believe that pragmatic researchers are capable of addressing far more diverse research questions, embarking on collaboration and have the perspective to zoom in and out of findings where relevant as they are au fait with both subjective interpretivist and objective positivist paradigms, i.e. pragmatic researchers have an intersubjective relationship with the research process (Morgan, 2007).

3.4 Research design

The methodological approach of this study is mixed methods, whereas the research design of this study is design-based research. According to Williams (2007), a strength of mixed methods is that "researchers are now able to test and build theories". This methodological approach therefore fits well with the decision to undertake design-based research in this study. In fact, mixed methods is the most favoured methodological approach in design-based research in that varied and changing forms of data can be collected as the study is refined (Anderson & Shattuck, 2012; Design-Based Research Collective, 2003; Ryu, 2020). Pragmatism underpins both the methodological approach and the research design chosen in this study (Wang & Hannafin, 2005; Anderson & Shattuck, 2012).

3.4.1 Mixed methods

Mixed methods represents using both qualitative and quantitative data collection tools and analysis to answer the research questions (Creswell, 2014; Teddlie & Tashakkori, 2009; Tashakkori, Johnson,

& Teddlie, 2020). Johnson & Onwuegbuzie (2004) argue that mixed methods result in superior research due to the blend of the most useful aspects of qualitative and quantitative methodologies.

As stated in the previous section pragmatism and mixed methods are aligned to the same ends: fully answering the research questions, which are as follows:

1. What were the barriers to understanding emission spectroscopy and how were they identified?
2. How were the barriers to student understanding of emission spectroscopy addressed?

A mixed methods approach was chosen so that the researcher could decide on the most appropriate means to answer the research questions above. Teddlie and Tashakkori (2010) refer to this as methodological eclecticism. In this study, the methodological approach was more specifically a sequential, explanatory mixed methods design as first described by Creswell (2003). Initially in this study, large scale quantitative data was collected and analyzed broadly to gain insights into potential barriers to students' understanding of emission spectroscopy. The approach changed over the course of the study and qualitative methods where then used to more fully explain, identify, and address the barriers that students were facing. More weighting was given to the qualitative findings and the inferences that could be made by the researcher because of their richness and depth.

The strength of this type of research is that mixed methods allows one the opportunity to fully explore the data at hand and also to verify findings using different methodologies (Onwuegbuzie & Leech, 2005). Another advantage of mixed methods is the diversity of analysis techniques available to the researcher, in that deductive and inductive analysis may be used in the same study (Johnson & Onwuegbuzie, 2004).

3.4.2 Design-Based Research

Design-based research has come to the forefront in educational research and is being "increasingly utilized" (Anderson & Shattuck, 2012). In short, design-based research is a methodology that seeks to understand "how, when, and why educational innovations work in practice" (Design-Based Research Collective, 2003).

"The pragmatic approach is to rely on a version of abductive reasoning that moves back and forth between induction and deduction—first converting observations into theories and then assessing those theories through action" (Morgan, 2007, pp. 71). This definition of pragmatism underpins the essence of design-based research, although the sequence may not be the same (see Figure 9). Design-based research begins with the analysis of a problem followed by identifying relevant theory for the hypothesis of a solution in practice, iterative cycles of testing and refining the solution alongside reflections which enhance both practice and the theory (Reeves, 2006).

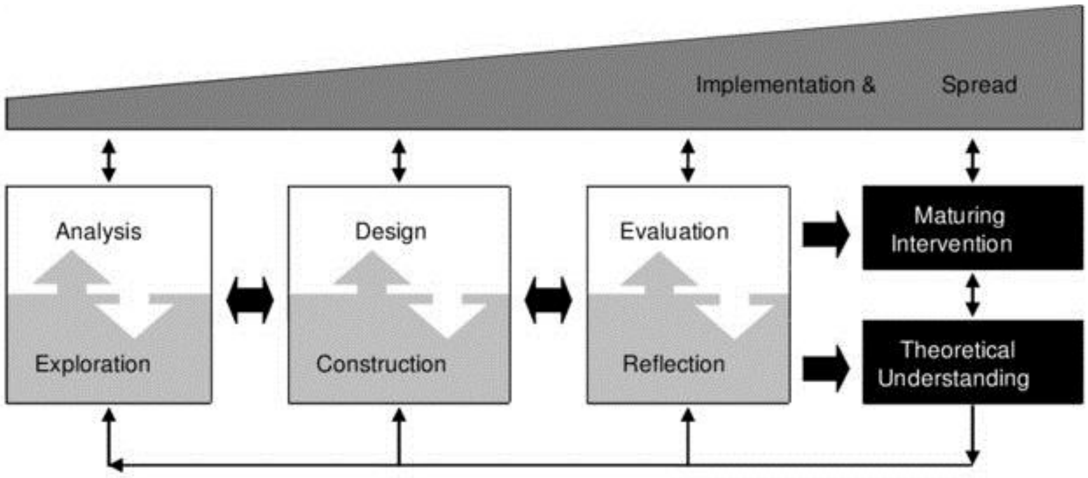


Figure 9. Summary of design-based research approach taken from McKenney and Reeves (2012)

The first goal or characteristic of design-based research is the intertwined design of learning environments with the development of learning theories (Design-Based Research Collective, 2003). According to Barab (2014), Design-based research is:

> “a form of research that can provide rigorous empirical grounding to theoretical claims and explanations and that can be more illuminative and useful to others because of its emphasis on exposing mechanisms and its articulation of the conditions through which these mechanisms were realized” (pp. 152, 153).

Design-based research “occurs in the buzzing, blooming confusion of real-life settings where most learning actually occurs” (Barab & Squire, 2004, pp. 4). Juuti and Lavonen (2006, pp. 55) acknowledge scepticism surrounding this new research design as all variables cannot be controlled or accounted for, “The appreciation of quasi-experimental research design is natural: science teachers and science education researchers tend to begin their studies in physics, chemistry, or biology, where an (quasi) experimental setting is conventional.” Design-based research surpasses the usual quantitative or experiential studies, which generally focus on the summative findings of an intervention, because the richness of a design-based research study adds to the rigour of the findings in learning context, enhancing the utility of the findings for researchers and practitioners (Wang & Hannafin, 2005). McKenney and Reeves (2013, pp. 97) succinctly summarise this ideal as follows, “One of the main goals of design-based research is to generate a theoretical understanding that can be of value to others.”

Design-based research is still developing as a methodological design to frame research studies (Design-Based Research Collective, 2003). There are limitations to the use of this design including the notion that knowledge generation is more complex than merely conveying teaching experiences, "In order to obtain knowledge, teaching actions need to be reflected (on). By means of reflected action, an experience becomes knowledge" (Juuti & Lavonen, 2006, pp. 58). McKenney and Reeves (2013, pp. 98) critique most design-based research studies to be "insufficiently mature to warrant reports of their specific impact (knowledge) on practice". A contrary view is provided by Anderson and Shattuck (2012, pp. 24) who feel that even immature design-based research that show small knowledge changes can still have long-term significance. Similarly, Barab (2014, pp. 159) cautions design-based researchers against being overly concerned with "return on investment" i.e. researchers should not "not overly focus on theory building research at the expense of scalable and sustainable impact."

Wang and Hannafin (2005) point out other challenges with design-based research including "varying levels of discipline and rigor" across design-based research studies and a lack of clarity on when the iterative cycles are working or should be abandoned. Furthermore Barab (2014, pp. 158) refers to challenges in describing the findings from a design-based research study "in a way that allows others to understand how to recontextualize them with respect to their local particulars" and secondly, design-based research is "unlike experimental design, it becomes difficult to rule out alternative explanations."

Be this as it may, the usefulness of using design-based research remains prominent in the educational context, surpassing action research due to the reverence with which theory is used to inform the iterative cycles (Anderson & Shattuck, 2012). This study reflects all of the five basic characteristics of design-based research as outlined by Wang and Hannafin (2005):

- **Pragmatic:** This paradigm aligns with the researcher's world view and quest for "practical answers to questions that intrigue the researcher" (Teddlie & Tashakkori, 2009).
- **Grounded:** The cognitive theoretical lens was used extensively from the onset of the study and continued to be used to inform and interpret findings.
- **Interactive, iterative, and flexible:** The researcher directly participated in the study, as she was also the lecturer i.e. the relationship between researcher and practitioner was as close as possible. Five iterative cycles were used over several years, to gain an understanding of students' barriers with spectroscopy. The structure of the laboratory exercise also changed with time.

- **Integrative:** Mixed methods were used to explore the students' understanding. The data collection tools evolved with researcher's needs to gain insights at different stages of the study.
- **Contextual:** The complex laboratory setting of this study included students from a variety of backgrounds, levels of exposure to laboratory settings and language proficiencies. The research design did not aim to control for any of these variables but looked at barriers to spectroscopy in a natural environment.

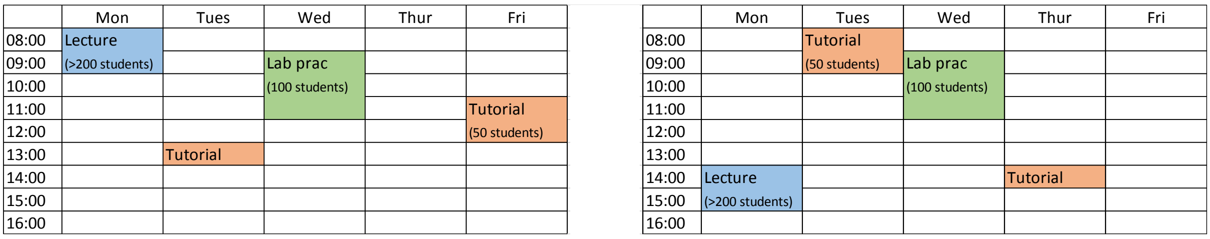
3.5 Context of the study

As explained in Section 1.3, all participants came from the extended programme of the University of Pretoria. Participants were diverse in terms of race, gender, home language, high school background and socio-economic status. Students on this programme usually do not meet the entrance requirements to complete their degrees in minimum time. In general, these students were characterised as novice and English second language speakers (ESL). ESL was used in this study as a collective term for all students without English as first language, irrespective of whether they may regard it as their third, fourth or other language. Prior to this study, there was no complementary laboratory exercise in emission spectra. The laboratory exercise was an addition to the extended programme curriculum to enable meaningful learning. Please see Appendix A for further details on the size, structure and use of the Mini Spec by the students in this study.

3.5.1 Structure of the course and curriculum

Teaching and learning activities relating to spectroscopy and emission lines are allocated one week within a fourteen-week long semester course, CMY 133. Students are exposed to formal teaching on the topic on a Monday during a two-hour lecture slot. 200-250 students attend lectures either in the morning or afternoon session. The lecture covers the basics of energy, spectra, the Bohr model of the atom and details the movements of electrons between energy levels. The lecture is interspersed with anonymous multiple-choice clicker questions and peer collaboration is encouraged.

From Tuesday to Friday, students on the extended programme are required to attend 3 hours in tutorial sessions. The tutorial groups contain the same 50 students for the duration of the year. The lecturer prescribes a set of problems of increasing difficulty for students to complete during the tutorial session or as homework. The tutorial sessions are facilitated by a senior tutor who encourages student interaction and peer learning. In addition to the tutorials and lectures, students attend one three-hour laboratory session, every second week (see Figure 10). The laboratories can only accommodate approximately 100 students at any given time i.e. two tutorial groups. Five laboratory sessions run per week to accommodate the 400-500 students enrolled per annum.



	Mon	Tues	Wed	Thur	Fri
08:00	Lecture				
09:00	(>200 students)		Lab prac		
10:00			(100 students)		
11:00					Tutorial
12:00					(50 students)
13:00		Tutorial			
14:00					
15:00					
16:00					

	Mon	Tues	Wed	Thur	Fri
08:00		Tutorial			
09:00		(50 students)	Lab prac		
10:00			(100 students)		
11:00					
12:00					
13:00					
14:00	Lecture			Tutorial	
15:00	(>200 students)				
16:00					

Figure 10. Timetables of two chemistry students allocated to different tutorial groups, both having the same laboratory practical slot

The teaching of spectroscopy falls in the middle of the students' first semester at university. Students' understanding of the content covered in this week prepares them for substantial subsequent topics in the curriculum such as the basics of quantum mechanics. In total there were five desired learning outcomes for emission spectroscopy as pre-defined in the curriculum:

- Understanding the basic functioning of a spectroscope
    1. The slit, as the focusing component (LO1)
    2. The wedge of CD, as the diffraction grating (LO2)
- Examining spectra from visible light sources
    3. Understanding how emission lines are formed (LO3)
    4. Classifying the type of emission spectra using the macroscopic descriptors of continuous or discrete (LO4)
    5. Interpreting emission spectra as evidence of the quantized electronic structure of the atom (LO5)

3.5.2 Outline of the laboratory session

Each laboratory session begins with a ten-minute pre-lab talk conducted by a laboratory demonstrator. The laboratory demonstrators are trained weekly prior to the experiment regarding relevant safety protocols and procedural information. Laboratory demonstrators were also reminded of key theoretical concepts during training. The information is shared by the laboratory demonstrators with the students during the lab talk. In the case of this laboratory experiment, the training included the construction and correct use of a Mini Spec; this training was vital as incorrect construction or use would result in students observing poor spectral lines or none at all. During training, the laboratory demonstrators were reminded about correct terminology to use along with the significance of spectral lines in terms of the first-year chemistry curriculum.

Several days prior to the scheduled laboratory experiment, a written laboratory procedure and a skeleton report sheet are uploaded online so that the students can begin with necessary preparations outlined within, e.g. compulsory reading or recommended YouTube videos. In the case of this laboratory exercise, students were required to complete two pre-lab activities before they would be granted access into the laboratory session (see Appendices C and D, pp.1).

The laboratory procedure guided the students in the construction of the Mini Spec. Students were welcome to consult with peers, laboratory demonstrators or academic staff during the construction process. Students were required to have their Mini Specs evaluated by the laboratory demonstrator to ensure adequate quality of their subsequent spectra observations. Students were required to observe spectra from four different light sources (incandescent, fluorescent, energy saver and sunlight) and indicate their observations in the table provided in their report sheet. Each student was required to hand in a report sheet at the end of the laboratory session. The report sheet structured students' observations and included questions on the components of the Mini Spec and the significance of their observations.

3.6 Overview of the study

The intention of this study was to identify and address barriers to understanding emission spectroscopy for novice university students in a laboratory setting. The process of selecting participants, gathering findings, and refining the laboratory exercise was facilitated over five cycles of implementation of design-based research.

3.6.1 Participants and sampling

Approximately 400-500 first-year chemistry students were enrolled in the chemistry course each year. In cycles 1 and 2 all students had the opportunity to participate voluntarily in completing the pre-lab and post-lab questionnaire. The final participation rates from cycles 1 and 2 are given in Table 2. Cycle 3 comprised of 9 students who had completed the course already; all students from cycle 3 were in their third semester and volunteered to be part of the study after-hours. Students from cycle 3 participated in all the data collection methods. These students were therefore more mature and had already encountered the topic a year prior, however, these students had not had exposure to the refined report sheet as the report sheets from cycle 1 and 2 were far more basic.

Table 2. Number of voluntary participants for the questionnaire administered in cycles 1 and 2

	Cycle 1: Pre-lab	Cycle 1: Post-lab	Cycle 2: Pre-lab	Cycle 2: Post-lab
No. of students enrolled	481	481	497	497
Number of responses (raw)	466	398	442	376

	Cycle 1: Pre-lab	Cycle 1: Post-lab	Cycle 2: Pre-lab	Cycle 2: Post-lab
Number of responses (cleaned)	443	358	425	332
Response rate (cleaned/enrolled)	92.1%	74.4%	85.5%	66.8%

The participants in cycles 4 and 5 were selected in a random yet stratified fashion: as students completed the laboratory exercise at different times, the laboratory demonstrators asked clusters of students who handed in their report sheets at similar times whether they would be interested in participating in the collaborative post-lab activity. Thus cycles 4 and 5 had clusters of students who finished rapidly, in moderate time or took longer times to finish the activity. The clustering in terms of time taken was assumed an indicator of students who may be on similar levels of understanding in spectroscopy. In total 52 students participated in total for cycles 4 (*N* = 20) and 5 (*N* = 32), however, only 48 report sheets were collected from cycles 4 and 5, (*n* = 19) and (*n* = 29) respectively.

3.6.2 Data collection instruments

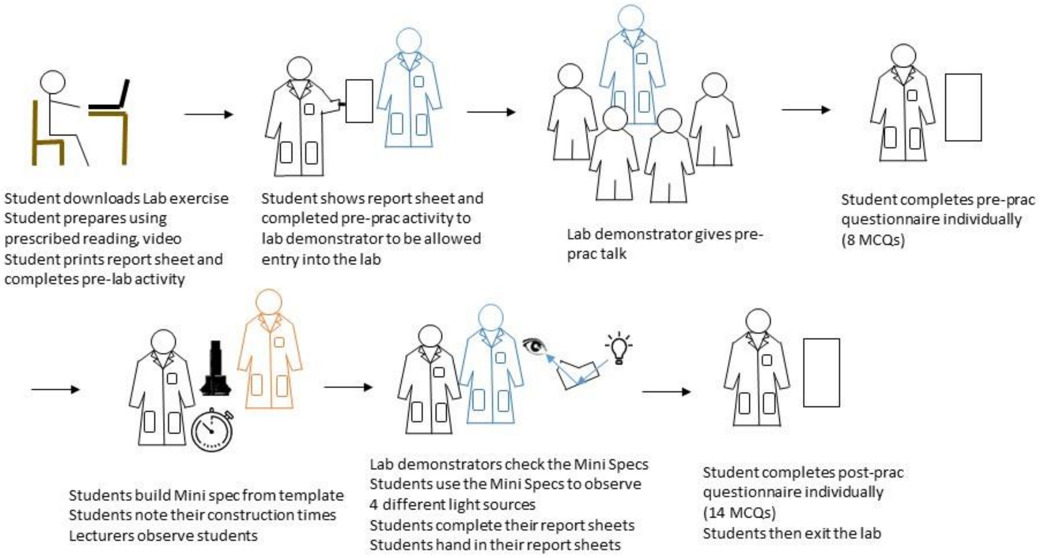
Data collection instruments are included as Appendices C-J. These include the time taken to construct the Mini Spec, performance in the report sheet, observation by lecturing staff prompted by a check list, a pre-lab questionnaire, a post-lab questionnaire and a collaborative post-lab group activity. However, not all data collection instruments were used in all five cycles, nor did the format of the data collection instruments necessarily remain the same. All students were required to complete the laboratory exercise which included two pre-lab activities, the construction of a Mini Spec and the completion of a report sheet. Participation in the pre-lab questionnaire, post-lab questionnaire and collaborative post-lab activity was voluntary.

A **pre-lab questionnaire** was given to each student as they entered the lab, however, participation was voluntary. In cycles 1 and 2, the pre-lab questionnaire consisted of eight multiple-choice items. The first item sought to gauge the student's level of exposure to optical tools and demonstration of their use; the remainder of the questions were based on the SpecUP Educational Spectrophotometer Questionnaire (Forbes, 2016). Access to this questionnaire was granted by the author. Questions from the prescribed textbook (Kotz, Treichel, Townsend, & Treichel, 2019) were also used. As the original pre-lab and post-lab questionnaires were based on selections from known published instruments, no tests for internal validity (usually factor analysis) or reliability (usually Cronbach's *alpha*) were performed. In cycles 3, 4 and 5, the pre-lab questionnaire consisted of one multiple-choice question devised by Ivanjek et al. (2015a), this item used simplified terminology yet touched on all the types of misconceptions described in their research. An open-ended follow-up question asking students to give reasons for their choice was included. Students were allocated 15 minutes to complete the pre-lab questionnaire; students who finished before the allocated time or chose not to participate could begin preparing their benches for the experiment.

A **post-lab questionnaire** was given to students upon the completion of the laboratory exercise; but completion was again voluntary. In cycles 1 and 2, the pre-lab questionnaire consisted of fourteen multiple-choice items (see Figure 11 and Figure 12). The first two items sought to gauge the students' perceived level of proficiency in constructing the Mini Spec; the next five items gauged students' confidence and motivation. The remainder of the questions were identical to those given in the pre-lab questionnaire). In cycles 3, 4 and 5 the post-lab questionnaire included the same singular multiple choice item from Ivanjek et al. (2015a), accompanied by an open-ended follow-up question that asked students to give reasons for their current choice compared to their choice in the pre-lab questionnaire. Students were allowed as much time as required to complete the post-lab questionnaire; once students completed this they were welcome to exit the laboratory.

The **collaborative post-lab activity** was only used to collect data from cycle 3 onwards (see Figure 13). Unlike the pre- and post-lab questionnaires which were individual tools, this was a voluntary group activity. Groups of two to five students elected to participate in the collaborative group activity. The average group size was approximately 3 students. Four items were included in the collaborative activity, the first two items dealt with the type of spectra and where taken directly from the pre-/post-lab questionnaire from cycles 1 and 2. This activity also included the same multiple choice item from Ivanjek et al. (2015a), along with a follow-up question which prompted students to discuss the rejected options and attempt to correct them. The students' discussion of the entire activity was recorded in the absence of the researcher, as the researcher was also the lecturer. The groups were left to facilitate themselves to decrease potential bias or uncomfortable and non-productive dynamics. The recordings were transcribed by an external party familiar with general chemistry. The researcher then verified the transcriptions against the recordings. If students elected to participate in the collaborative activity, their **report sheets** were also collected for data analysis. These report sheets where photocopied and scanned for hard copy and digital storage, respectively.

On the next page are schematics of the sequences laboratory session interspersed with data collection. The stages shown in Figure 11 are fully annotated. Students are represented in black; laboratory demonstrators are in blue and lecturing staff are in orange. Figure 12 and 13 follow the same stylising as Figure 11; however, annotations are only used when the stages differ from those given in the preceding figure. Further details on the cycles of implementation are given in the next sub-section.



Student downloads Lab exercise
Student prepares using prescribed reading, video
Student prints report sheet and completes pre-lab activity

Student shows report sheet and completed pre-prac activity to lab demonstrator to be allowed entry into the lab

Lab demonstrator gives pre-prac talk

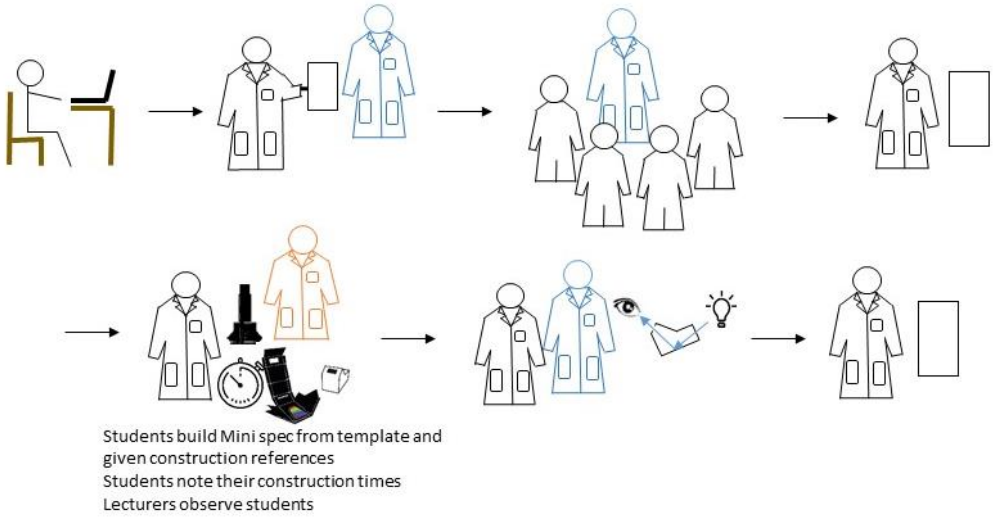
Student completes pre-prac questionnaire individually (8 MCQs)

Students build Mini spec from template
Students note their construction times
Lecturers observe students

Lab demonstrators check the Mini Specs
Students use the Mini Specs to observe 4 different light sources
Students complete their report sheets
Students hand in their report sheets

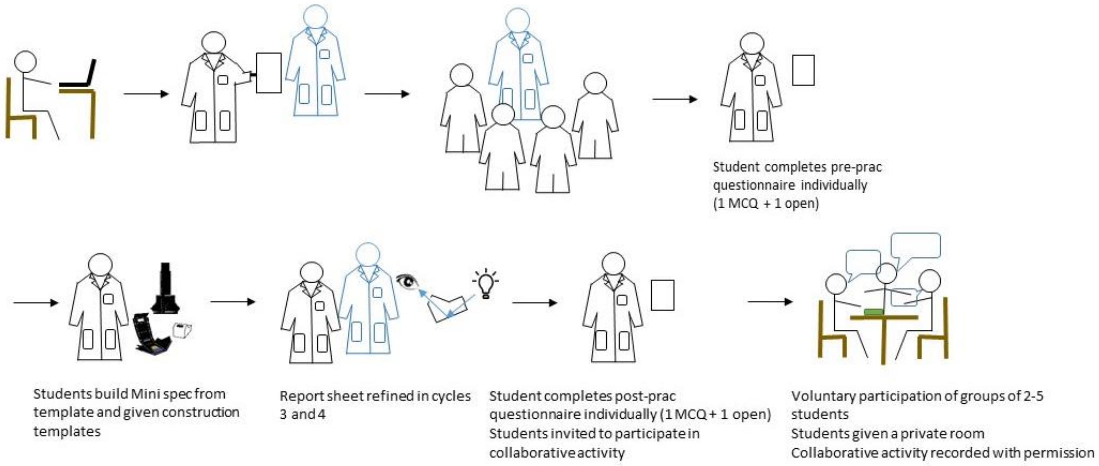
Student completes post-prac questionnaire individually (14 MCQs)
Students then exit the lab

Figure 11. Summary of the sequence of laboratory exercise and data collection methods in cycle 1



Students build Mini spec from template and given construction references
Students note their construction times
Lecturers observe students

Figure 12. Summary of the sequence of laboratory exercise and data collection methods in cycle 2



Student completes pre-prac questionnaire individually (1 MCQ + 1 open)

Students build Mini spec from template and given construction templates

Report sheet refined in cycles 3 and 4

Student completes post-prac questionnaire individually (1 MCQ + 1 open)
Students invited to participate in collaborative activity

Voluntary participation of groups of 2-5 students
Students given a private room
Collaborative activity recorded with permission

Figure 13. Summary of the sequence of laboratory exercise and data collection methods in cycles 3-5. The Report sheet was revised from cycle 3 to cycle 4. Minor word changes were made to the report in cycle 5.

3.6.3 Cycles of implementation

Five iterative cycles of design-based research were undertaken to attempt to identify and address the barriers faced by students. The flexible nature of design-based research allowed for changes in the types of data collection tools and refinements to the laboratory exercise. The five cycles were spread over 4 years. Cycles 1 and 2 were a year apart differing only in that construction references were supplied in addition to written instructions on how to build the Mini Specs in cycle 2 (see Figure 14); the methods of data collection remained the same (see Figure 11 and 12, and details given in Table 3). A full year was taken to analyse and reflect on the findings of cycles 1 and 2; a paper was written describing the effect of the introduction of the construction references on student performance, construction time and the spontaneous outreach that resulted from students' sense of empowerment and growth of scientific identity based on the Mini Spec laboratory exercise (see Appendix A).

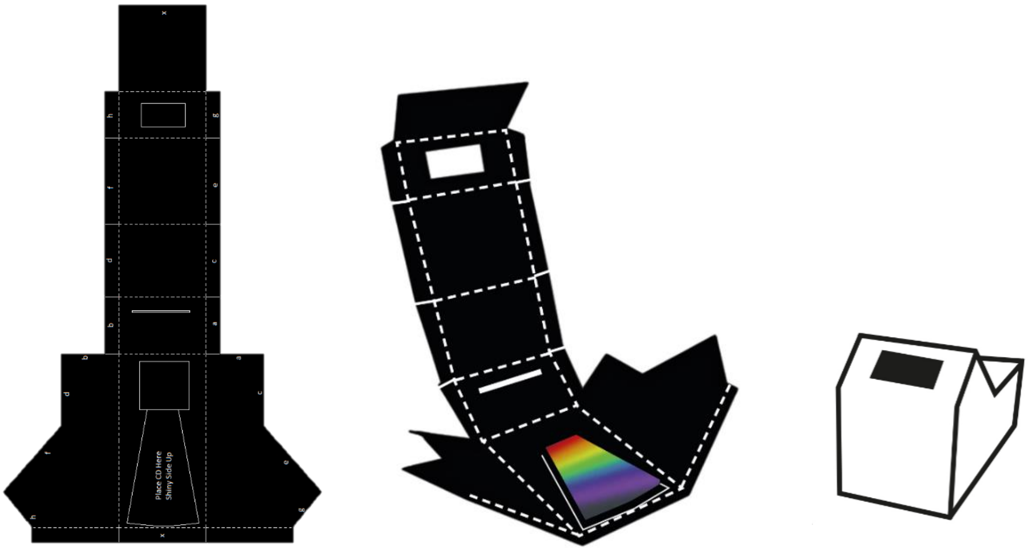


Figure 14. Mini Spec template (left) and two construction references (right) (Mundy & Potgieter, 2020)

Despite these positive findings, the pre- versus post-lab questionnaire showed no significant improvements in students' conceptual understanding. During the year of analysis and reflection, design-decisions were made to completely overhaul the questionnaires and the report sheet (more detail is given in Chapter 4). As stated previously, cycle 3 was a small-scale and low-stakes sample as they had already completed the course in the previous year, therefore the ideal sample for the many changes envisioned for cycle 3. Cycle 4 was implemented with in-semester students two months after the completion of cycle 3. Cycle 4 mimicked cycle 3 in format however, refinements were made to the report sheet based on analysis and reflection (see Table 3). At the time of implementation of cycle 4, the researcher discovered a finding that lead to a 'just-in-time' design-decision to alter one word in the pre-lab, post-lab and collaborative activity. This design-decision precipitated substantial findings that helped understand and address the barriers faced by students (see section 4.2.3 in the next chapter). Therefore, cycle 5 is not truly a separate cycle from cycle 4, the students were from the same cohort. The only difference between cycles 4 and 5 was the replacement of a single word in three of the data collection tools, no changes were made to the report sheet. However, the magnitude of the findings based on this design-decision has led the researcher to present cycles 4 and 5 separately, even though they do not strictly follow the process of design-based research cycles. The researcher has summarised the changes from cycle to cycle in Table 3; this Table speaks to Figures 11, 12 and 13.

Table 3. Summary of the five cycles of design-based research

	Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5
Year	2016	2017	2019	2019	2019
Course	In semester	In semester	Out of semester	In semester	In semester
Number of participants	443	358	9	19	29
Construction of Mini Spec	Written Instructions	Written Instructions + construction references	Written Instructions + construction references	Written Instructions + construction references	Written Instructions + construction references
Structure of report sheet	1. Pre-lab activity 2. Observation table 3. 1x question on significance of findings	1. Pre-lab activity 2. Observation table 3. 1x question on significance of findings	1. Pre-lab activity 2. Observation table 3. 2x questions on components of Mini Spec 4. 2x questions on significance of findings	1. Pre-lab activity 2. Observation table – *expanded* 3. 2x questions on components of Mini Spec *(scaffolded)* 4. 2x questions on significance of findings *(scaffolded)*	1. Pre-lab activity 2. Observation table *(expanded)* 3. 2x questions on components of Mini Spec *(scaffolded)* 4. 2x questions on significance of findings *(scaffolded)*
Pre-lab questionnaire	8 MCQ	8 MCQ	1 MCQ 1 open item	1 MCQ 1 open item	1 MCQ *(wording refined)* 1 open item
Post-lab questionnaire	14 MCQ 1 open item	14 MCQ 1 open item	1 MCQ 1 open item	1 MCQ 1 open item	1 MCQ *(wording refined)* 1 open item
Collaborative activity	No	No	Yes 3 groups	Yes 5 groups	Yes *(wording refined*) 10 groups

3.7 Ethical Considerations

Ethical clearance was granted for this study by the Faculty of Natural and Agricultural Sciences at the University of Pretoria (reference number 180000144, see Appendix M). This study did not aim to benefit one group of students above another group but aimed at improving student learning with each cycle. Students from earlier cycles were not disadvantaged by the study, this was not an experimental or quasi-experimental design. All interactions with the laboratory exercise gave students the opportunity to interact with spectroscopy in a hands-on manner that did not exist before this study.

It must be reiterated that all students who participated in this study, by answering the pre- or post-lab questionnaires, allowing the analysis of their report sheets or by engaging in the collaborative activity, did so on a voluntary basis. All students were provided with an information sheet detailing the tasks required for participation in the study along with an informed consent form (see Appendices N and O). Students were made aware that they were able to withdraw from the study at any time without any negative repercussions. A withdrawal from the study would imply the removal and destruction of any data pertaining to the participant, however, there were no withdrawals of participation.

In terms of data collection and handling, only data relating to understanding and learning barriers was collected. Demographic data was not required for this study. Once the data was collected, the information was de-identified and participant numbers were allocated e.g. P1, P2, P3 etc. The data was stored electronically and protected from unauthorised access or use using a password protected computer file, the code known only to the researcher (links to protected versions of this data can be found in Appendices P and Q). De-identified hardcopy data resides securely with the researcher and will be destroyed 15 years after the conclusion of the study.

3.8 Analysis and Reflection

Analyses and reflection are presented alongside each other in this section in line with the principles of design-based research. Analyses of all the pre-lab and post-lab questionnaire multiple choice items was done using descriptive statistics in cycle 1. This analysis revealed little or no gains after completing the laboratory exercise. Anecdotal staff observations prompted the design-based decision to include construction templates to help students build their individual Mini Specs in cycle 2. Inferential statistics, e.g. *t*-tests, were used to compare students' construction time and report sheet performance across the two cycles. Although a significant difference was seen in these two instances, students again showed no improvement in performance from the pre-lab questionnaire to the post-lab questionnaire.

These findings appeared incongruent with the implemented design-based decision, therefore 2018 was taken as a year to reflect on findings, to this point. The reflection led to changes in the research design that resulted in extensive modifications of the laboratory exercise. The reflection also led the researcher to the realization that she required greater insight into the understanding of the students and the barriers they were facing, resulting in the design-decision to introduce a recoded collaborative activity and gather students report sheets for individual analysis. Cycle 3 was critical for gathering findings on the modifications. Cycle 3 had nine third semester participants who had completed the course the previous year, therefore this cycle was considered small-scale and low stakes as students had already passed CMY 133 the first semester course in chemistry.

From cycle 3 onwards analysis shifted to a qualitative focus. A brief first round of analysis focusing on the students' collaborative recordings in cycle 3 for instances of sense-making and sense-breaking led the researcher to believe that language *may* indeed be a barrier to students understanding. Therefore, a small alteration to wording in cycle 5 was decided (the word "jumps" was replaced with "drops" for the pre-lab questionnaire, post-lab questionnaire and collaborative activity).

After all data was collected from cycles 3, 4 and 5, the researcher begun the intensive process of coding the report sheets and transcripts of the collaborative activity. Atlas.ti 8 was used to perform reflexive coding, which constantly re-aligning coding to the aim of study whilst being open to emerging insights. Analytic coding memos were completed periodically to document insights and new codes as the researcher's thinking changed (Saldaña, 2021). These memos can be found in Appendix K.

Initially the researcher tried to allow barriers to emerge from the coding process, however, this process did not readily evaluate the degree of students' understanding in emission spectroscopy. After engaging with the data for a substantial period of time, the researcher decided to use the curricular learning outcomes to inform the coding process of the report sheets. The unit of analysis was student sense-making according to the learning outcomes of the course. The level of sense-making was finally coded as either poor, partial and good understanding of each relevant learning outcomes based on the written report sheet submissions (see Chapter 4, Table 4). Codes of developing or partial understanding were particularly useful in identifying and addressing three primary barriers to student understanding. Learning outcome 3 was tracked using students' closed responses to the pre- and post-lab instead and are therefore this learning outcome is not included in the table (see Chapter 4, Table 4).

Once the coding had been decided upon, an in-depth analysis of the findings was done exclusively for cycle 5 (see Chapter 5). The flow of students understanding from one learning outcome to another was analysed using Sankey graphs. Additionally the collaborative activity was coded for instances of sense-making and sense-breaking, allowing the researcher to reflect on the growth of student understanding to gain further insights into persistent learning barriers after five cycles of design-based research.

3.9 Quality Criteria

3.9.1 Validity

According to Creswell and Miller (2000) credibility or validity of research may be judged by the duration for which the researcher engages with the study. In the instance of this study, the researcher engaged with the study over five cycles, spanning several years. Multiple sources of data including construction time, performance in the report sheet, observations by lecturing staff, a pre-lab and post-lab questionnaire, and a collaborative post-lab group activity, were used in this mixed methods approach which allows for further credibility in that the findings from various data sources were triangulated against each other. The researcher also engaged with findings and reflected on the emergent coding for more than a year before deciding on a final coding rubric (see Chapter 4, Table 4).

Specifically, in terms of the report sheet responses and collaborative recordings, vignettes were reproduced verbatim in Chapter 4 and 5, allowing the reader to determine the truth value (validity) of the researcher’s interpretations (Noble & Smith, 2015). The report sheets are a standard form of course assessments, a usual concern with course assessments is that they may introduce bias and compromise the validity of the findings in that students may be seek to gain marks instead of exhibit understanding, however, the design of the emission spectroscopy report sheets was purposeful in assigning marks for exhibiting understanding.

In terms of design-based research, the rich context of the study (positioned in the extended programme with ESL students) lends validity to the findings, and instead of narrowing the transferability of the findings, the specific context of this study allows the reader to interpret the knowledge generated and decide for themselves the applicability in their own contexts (Anderson & Shattuck, 2012). In fact, design-based research is an emerging field in chemistry education literature, allowing the community to engage with principles such as LEPO (learning environments, processes and outcomes) in their own contexts (Lawrie, Grøndahl, Boman, & Andrews, 2016).

Finally, the lecturer was also the researcher therefore bias cannot be fully removed, in fact the ability of the practitioner to inform the decisions of the researcher adds again to the contextual richness of the study, that is, “inside knowledge adds as much as it detracts from the research validity” (Anderson & Shattuck, 2012, p. 18)

3.9.2 Reliability

The reliability of the coding from cycle 3 to 5 was verified using the process of member-checking. The Spearman's *rho* coefficient was used to determine the correlation between the researcher’s coding of the level of understanding of the learning outcomes compared with a second coder (the supervisor in this case). Spearman's rho (r_s) was used instead of Pearson’s R because the data is ordinal (codes assigned were 1-poor, 2-partial and 3-good understanding). Therefore, the data was distribution-free i.e. had no statistical distribution around a mean and as such a non-parametric measure of correlation needed to be used (Hauke & Kossowski, 2011).

The closer r_s is to zero, the weaker the strength of the correlation. Correlations can be positive or negative; a positive correlation was expected between coders. A brief guideline for interpreting the strength of r_s values according to the BMJ (2020) is as follows: very weak (r_s = 0.00 - 0.19), weak (r_s = 0.20 - 0.39), moderate (r_s = 0.40 - 0.59), strong (r_s = 0.60 - 0.79) and very strong (r_s = 0.80 - 1.00). The second coder was supplied with instructions to code one third of the report sheets at random according to the first draft of the coding rubric. The correlation coefficients between the coder and the researcher were 0.22 for LO1, 0.63 for LO2, -0.10 for LO4 and 0.84 for LO5 in after the initial round of coding. The researcher and the second coder discussed the differences in assigned coding, especially for LO1 and LO4 where the rubric did not convey acceptable cues to code partial or developing understanding. The coder and the researcher jointly refined the coding rubric. The process was repeated a second time with the researcher and the second coder re-applying the rubric to another random selection of one third of the remaining report sheets. Again, discussions occurred, and the rubric was further refined. All 57 report sheets were re-coded by both the researcher and the second coder.

After the final round of coding and discussions the level of agreement between the coders improved to 0.86 for LO1, 0.95 for LO2, 0.84 for LO4 and 0.95 for LO5. All correlations between coders were both very strong and statistically significant $p < 0.01$ in the final round of coding (more information can be found in Appendix L).

In chapter 5, students’ overall performance over the course of the semester, i.e student's final mark for the module, was used against their coded understanding for LO5 in an effort to prove that students who were successful in communicating their sense-making were not merely top performing students.

3.9.3 Bias

In preparing the students to participate in this study, the study was introduced to the entire student cohort at least 24 hours before the commencement of a laboratory session. This allowed students to process the significance of the study as well as what may be required of them well before deciding to participate. In cycles 1 and 2, almost the entire student population chose to participate in the quantitative portion of the study, the large numbers should minimize the bias that may be introduced by a smaller sample.

In cycles 4 and 5, students were invited to participate in the study just before the collaborative activity i.e. after completing the laboratory exercise. This preserves the integrity of their constructed report sheet answers in that students were not pre-occupied with their participation in the study while attempting to communicate their written responses. Additionally, the collaborative recordings were conducted in a private room in the absence of the researcher to put the students at ease and to stimulate more natural discussions around the tasks. Students were welcome to converse in other languages during the collaborative activity, however, only small interjections and assents were made in native languages. To reduce bias for the researcher, transcription of recordings was done by external parties and checked by the researcher.

The lab demonstrators identified and invited students from cycles 4 and 5 to participate based on the speed with which the students completed the experiment. The decision was made to distance the researcher from the participants to reduce sample bias and allow a representative cross-section of participants based on time taken to complete the experiment.

3.10 Limitations

The researcher acknowledges upfront that this study was confined to a laboratory experiment on emission spectroscopy. No analysis of the tutorials or lectures was performed; however, the findings of this study may have the potential to inform instances of better practice in the classroom (see Chapter 4). The researcher also acknowledges that a first-year extended programme chemistry course has a very specific pedagogy in terms of style, depth and pace; however, the transferability of understanding and addressing barriers to students' understanding in spectroscopy need not be limited by this as characteristics of novice students in other contexts may be the common denominator.

In terms of the data collected, some of the report sheets were illegible, and thus had to be discounted from the coding process. Nevertheless, these students' voices in the collaborative activity were still relevant. During the coding of the report sheets variations may occur due to unforeseen weaknesses in the coding rubric or the biases of the coders, however, great efforts were made to ensure that the coding across all five learning outcomes was equally rigorous.

The data collection process of this study spanned four years, during which time the size of the samples changed along with the data collection methods. Additionally, the experiences of the students across the cycles may also have varied; in fact, there are too many variables in a design-based research study of this magnitude to account for, but this in itself adds to the richness and contextual beauty of design-based research. The shifting nature of the study from predominantly quantitative in cycles 1 and 2 to more qualitative in cycles 3, 4 and 5 may make some audiences uneasy. Be that as it may, the findings from cycles 1 and 2 have already been published in a well-respected chemistry education journal (see Appendix A) and the thesis portrays the qualitative, deeper findings for interpretation and interrogation informed by the versatile theoretical framework of Cognitive Load Theory.

CHAPTER 4: Delving into the Findings of Design-Based Research

4.1 Introduction

The findings from five cycles of design-based research are presented in this chapter. The findings include data from a variety of data collection instruments: laboratory observations, student performance, time on task, pre-lab and post-lab questionnaires, student report sheets, and recorded post-lab collaborative activities. These findings are not presented per cycle but are presented in five subsections according to the five core spectroscopic learning outcomes of this study:

- Understanding the basic functioning of a spectroscope
    1. The slit, as the focusing component
    2. The wedge of CD, as the diffraction grating
- Examining spectra from visible light sources
    3. Understanding how emission lines are formed
    4. Classifying the type of emission spectra using the macroscopic descriptors of continuous or discrete. *At the same time, acknowledging spectroscopic signatures as unique to the source material*
    5. Interpreting emission spectra as evidence of the quantized electronic structure of the atom

Each learning outcome is presented separately with the changing findings over time, according to the principles of design-based research with the guidance of Cognitive Load Theory (see subsections 4.2.1 to 4.2.5). In terms of the changing findings over time, the reader must remember that cycles 1 and 2 differed greatly from the latter three cycles. The findings from the first two cycles were published, showing the positive effects of introducing construction references (see Figure 14) in cycle 2 to supplement student construction of their individual Mini Specs: students built their Mini Specs faster ($t(406) = 2.76$, $p = 0.003$, Cohen $d = 0.4$), spent longer engaging in the laboratory exercise and student performance in the report sheet improved ($t(405) = 3.98$, $p = 0.0005$, Cohen $d = 0.4$). Most importantly, students took their Mini Specs to their homes and communities. This spontaneous outreach was evaluated and showed positive effects on their audiences' interest in science and on the students' developing self-concept as scientists.

The findings presented from cycles 1 and 2 in this chapter show a very different picture as far as students' mastery of the five learning outcomes is concerned: there appeared to be no significant improvement from cycle 1 to cycle 2, nor from pre-lab to post-lab questionnaire responses in either cycle. These findings from cycles 1 and 2 are presented as a part of Section 4.2 to give background for the more scholarly determination to identify and address the barriers to student understanding of emission spectroscopy from cycles 3 onwards. The report sheet was altered to probe and scaffold student understanding. A collaborative activity was also included from cycle 3 onwards to elicit rich verbal transactions of sense-making and sense-breaking in this complex topic.

A rubric was developed to provide an evaluative framework for the researcher to use to quantify students' developing understanding of the emission spectroscopy in the report sheets and collaborative activity during the final three cycles. Where possible, the analysis of each of the learning outcomes was done by coding the data as either exhibiting good, partial or poor understanding according to the rubric (see Table 4). The construction of this evaluative framework in the form of a concise rubric was the result of immersion in the data, revisiting and reviewing codes (see section 3.7) and a rigorous member checking approach (see section 3.8.2). Learning outcome 3 is not featured in Table 4 because quantitative data was the primary source used to evaluate students' understanding of spectral line formation (see section 4.2.3).

Reflection is an integral component of design-based research (Anderson & Shattuck, 2012), and for this reason, findings, discussions, and reflections are presented alongside each other in Chapter 4. In general, this design-based research study suggests improved student understanding of the principle learning outcomes after each of the cycles. This study aimed to contribute not only a refined laboratory exercise centred on the construction and use of a Mini Spec, but also a means to formally assess relevant student learning outcomes as called for by Kovarik et al. (2020).

Table 4. Evaluative framework in the form of a rubric for coding the students' understanding of the learning outcomes

	Code 1: Poor Understanding	*Code 2: Partial Understanding*	*Code 3: Good Understanding*
LO1: Slit and focus	Students attribute a completely inappropriate purpose or phenomenon to the slit	Students see the slit only as an entry point for the light into the Mini Spec. Students may note that the size of the slit manages the amount of light allowed into the Mini Spec. However, students do not show any further understanding in its role of focusing the incoming light.	Students may acknowledge the slit is an entry point for light but **must** acknowledge the narrowing or focusing function. Responses that included straightening or concentrating the amount of light were accepted as they attempted to convey the concept of focusing. "Blurred" when the slit is too large was accepted as it indicates the incoming light will be out of focus.
LO2: Diffraction Grating	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.	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 in physics may have angles other than 180^{o}.	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.
LO4: Continuous vs. discrete	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.	Students use the terms discrete or continuous correctly according to their observations. Students do not elaborate on the meaning of the terms or may assign incorrect meaning. This was noted with the term, discrete, where students think this means the absence of some colours and do not see discrete as definite bands.	Students show a strong 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 the colours. Discrete lines are described as dark spaces or lines.

	Code 1: Poor Understanding	*Code 2: Partial Understanding*	*Code 3: Good Understanding*
LO5: Intensity	Students give an inappropriate explanation of what spectral line intensity means. Students view intensity as a function of the source. Alternately students equate energy, frequency or wavelength of an emission line to intensity	Students see intensity as a function of probability or likelihood. But are uncertain or incorrect as to the probability of what? The terms “more of” and “more often” were indicators of this code. Students were not able to communicate that the frequency of electron transitions is the root of intensity. Students may say more of a certain wavelength, frequency or energy. This code shows students developing insight which they cannot fully communicate.	Students relate the intensity or brightness of a spectral line to the greater likelihood of an e^{-} transition occurring. Students realize that intensity relates to the **amount** of energy or the **same** photons released **per** unit of time.

4.2 The five learning outcomes

4.2.1 Component of the Mini Spec: The Slit

The Mini Spec is an extremely simplified spectroscope that can be built at very low cost with a relatively low skill level. The simplicity of the Mini Spec made it ideal in principle in the context of this study, as it should be less cognitively demanding than other more sophisticated spectroscopic tools. The learning outcomes related to the Mini Spec laboratory experiment were understanding the formation, and unique identity of emission spectra, and understanding the basic functioning of a spectroscope. The Mini Spec contains only the most vital components of a spectroscope needed for it to function: a focusing area (the slit), a diffraction grating (a wedge of CD) and an eyehole for viewing the resultant spectra.

There are several purposes for the slit, the most obvious is to allow light into the Mini Spec, however, an incision of any shape would allow light into the Mini Spec. The placement of the slit is also noteworthy as it allows light to be directed onto the wedge of CD. But, the ultimate purpose of the slit, and the desired learning outcome, is that the slit focuses the incoming light, i.e. it is the narrow shape of the slit that forces incoming light to converge in a high resolution beam (Ivanjek et al., 2020). The width of the slit must be ideal to focus the incoming light: too wide means too much unfocused light is allowed into the Mini Spec, too narrow means not enough light may enter the Mini Spec. Both of these instances would result in poor or confusing observations.

In cycles 1 and 2, students' understanding of the purpose of the slit was gauged using a fixed response item questionnaire item *based* on a prescribed textbook problem from Kotz et al. (2019) (see Appendices E and F). The questionnaire item from cycles 1 and 2 included "I am not sure" as the first option to allow students to select it freely, instead of having it as the last option. The questionnaire item also included an additional two distractors (D and F). The principle distractor was option F, to disperse light. The questionnaire item was completed for both pre- and post-lab in cycles 1 and 2. The number of student responses are given in Table 5 and translated into a graphical presentation showing percentages in Figure 15.

Original Textbook Problem: **What is the purpose of the slit?**

- **A.** Block emitted light
- **B.** **Make a narrow beam**
- **C.** Disperse the light

Table 5. Number of student responses to the questionnaire item, “The purpose of the slit is to:”

	Cycle 1: Pre-lab	Cycle 1: Post-lab	Cycle 2: Pre-lab	Cycle 2: Post-lab
A. I am not sure	31	14	28	18
B. Block emitted light	13	15	15	22
C. Dim the incoming light	19	28	19	28
D. Protect your eyes	9	12	9	13
E. Make a narrow beam	**272**	**234**	**284**	**217**
F. Disperse the light	99	55	70	42
Total	443	358	425	332

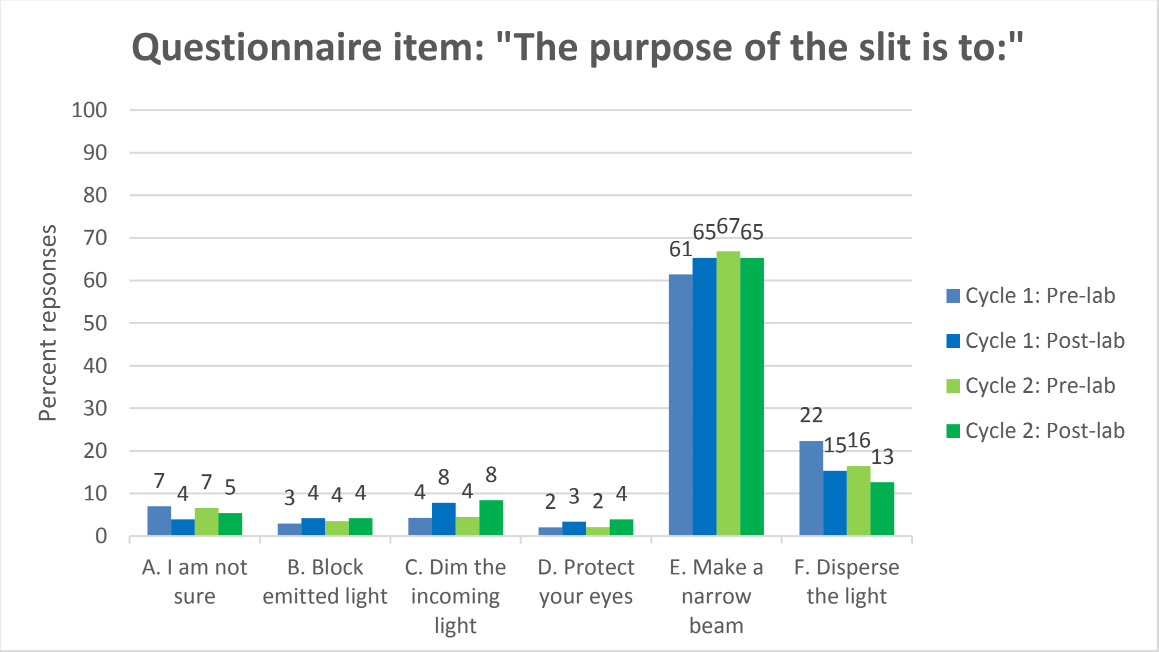


Figure 15. Graph of the percent of student responses to “The purpose of the slit is to:”

From Figure 15 it can be seen that prior to the laboratory practical in cycle 1, 61% of the students correctly selected the purpose of the slit as response E. After completing the practical, only 65% of students made the correct selection. After reflecting on cycle 1, it was proposed that the students might be overwhelmed by the complexities of building and operating the Mini Specs, i.e. the demand of the task may have been too high, especially as the majority of students were ESL. Thus, the first language related barrier was flagged namely: Interpreting written instructions. External observations by lecturing staff (see Appendix Q) indicated, “Students needed advice on where to cut, i.e. dotted or plain lines. One (student) started by sticking it (the Mini Spec) inside out”, thereby giving further evidence of high task demand.

A design-decision was made for cycle 2, to further minimise the extraneous cognitive load on students by supplementing written instructions with construction templates. The construction references improved students' construction speed and performance (see Appendix A), however, the construction references did not improve students' understanding of the purpose of the slit: the post-lab result of 65% correct was repeated in cycle 2. A constant percentage of students from cycles 1 and 2 also chose the principle distractor, option F. This may because it includes terminology associated with optics, however, it was suspected that ESL students do not have appropriate prior knowledge linked to this term and thus will be drawn to this distractor.

From cycle 3 onwards, the questionnaire item was removed and replaced with an open-ended question in the report sheet, ***"What is the purpose of the slit in your Mini Spec? What would happen if the slit was too large? Or too small?"*** Guiding this design-decision was collaborative Cognitive Load Theory and Social Constructivism: by asking the question in an open-ended format during the practical (not either pre- or post-lab) students were able to interact with their colleagues, demonstrators and academic staff to discuss the purpose of the slit. The second half of the question prompted some students to explore the physical parameters of the slit to help them construct meaning for the purpose of the slit in real-life without distractors from misunderstood optics terminology.

A total of 57 students' written responses to this question in their report sheets were analysed from cycle 3 to cycle 5. The responses were coded according to the rubric as either poor, partial or good understanding of the slit (see Table 6). The written responses show a positive shift towards more students understanding the purpose of the slit, at least in part or in full.

Table 6. Coding of students' written report sheet responses on the purpose of the slit for cycles 3, 4 and 5 (*n*=61).

Code	Representative written responses	Frequency (*n*=57*)
Slit and focus, Poor understanding Students attribute a completely inappropriate purpose or phenomenon to the slit	"The slit in the Mini Spec is used to absorb light" P41 "To reflect light from the source" P2 "The slit spreads the light into different wavelengths by different amounts" P17	4
Slit and focus, Partial understanding Students see the slit only as an entry point for the light into the Mini Spec. Students may note that the size of the slit manages the amount allowed into the Mini Spec. However, students do not show any further understanding in its role of focusing the incoming light.	"It acts as a pathway for light to pass through" P30 "The slit only allows a certain amount of light in to be analyzed" P27 "If the slit was too large, a lot of light would enter the Mini Spec" P36	31

Code	Representative written responses	Frequency (n=57*)
Slit and focus, Good understanding Students may acknowledge the slit is an entry point for light but **must** acknowledge the narrowing or focusing function. Responses that included straightening or concentrating the amount of light were accepted as they attempted to convey the concept of focusing. "Blurred" when the slit is too large was accepted as it indicates the incoming light will be out of focus.	"The slit focus(es) a beam of light directly onto the piece of CD" P25 "The slit controls the light that enters the Mini Spec… If the slit was too large, more light will enter, making the light blurry" P60 "The slits allows light to move in a straight line then fall on the CD" P37	22

*several responses were not coded due to missing data or the quality of the photocopied handwritten report sheets

Finally, a guided collaborative activity was introduced as a post-lab exercise from cycle 3 to cycle 5. These discussions were recorded with the students' permission. The reason for the inclusion of a collaborative post-lab activity was two-fold: firstly, a well-designed post-lab exercise may be an invaluable opportunity for students to examine the processes that they were exposed to in the laboratory i.e. spectral line formation (Reid & Shah, 2007). The second reason was that the collaborative nature of the task should enable students to use their joint working and long-term memories to make sense of complex concepts according to Collaborative Cognitive Load Theory (Kirschner et al., 2018). From the array of spectroscopic concepts, the post-lab collaborative activity provided a platform for some of the groups to discuss the purpose of the slit in retrospect after completing the practical experiment and report sheet. The rubric was also used to evaluate the students' efforts at group sense-making. The value of the collaborative activity can be seen below in the underlined portions from selected vignettes from the eighteen recorded group discussions across cycles 3 to 5.

Vignette 1. Excerpt from collaborative discussion, group 15, cycle 5

Male 1:	*What's the purpose of the slit? I'm just asking…*
Female 1:	*<u>To let the light in</u>, ja…*
Male 2:	*Obviously <u>to improve the resolution</u>*
Female 1:	*Ja, cause if you have too much light…*
Male 1:	*So if there was a question that asked if the slit was too large or too small? So if it's too large it would be bad resolution? If it's too small then the resolution would be poor. Because I did it the first time and my slit was too small to see the spectrum, then I made it bigger so I could continue with the experiment*

Vignette 2. Excerpt from collaborative discussion, group 6, cycle 5

Male: *(reads): "The most important conclusion from the spectrum from an energy saver globe is that:*
A. *Not sure*
B. *Energy is emitted over a wide range*
C. ***Emitted energy is discrete or quantized***
D. *The wedge of CD absorbs specific wavelengths of light*
E. *The slit prevents certain wavelengths of light from entering the mini spec"*

Male & Female 1: No, it can't be "E"
Female 1: *'Cause it ("E") says, "the slit prevents certain wavelengths"*
Female 2: *Ja, no. It (the slit) doesn't.*
Male: *No, no. What the slit does, it focusses light so that light, so that light is not scattered*
Female 2: *Oh (interjects)*
Female 1: *So it does (agrees with male)*

Vignette 3. Excerpt from collaborative discussion, group 1, cycle 3

Male 1: *Okay, but then it is out because you can't prevent light from coming in. We have the slit and the slit is there for the light to come in.*
Male 2: *But it is only a small amount of light, to only allow certain amounts of light.*
Female: *But the whole thing at the end of the day it's not like it's only allowing yellow light and red light*
Male 2: *But that small amount of light it carries everything that the huge amount of light carries. It has the same quantities.*
Male 1: *Then what is the reason for having a small slit if it has all the quantities. If the small light has all the same quantities of as big source of light?*
Female: *That's a good question…*
Male 2: *So that it can regulate the light so that we can see properly the reflections (means emission spectra).*

4.2.2 Component of the Mini Spec: The wedge of CD

There are two functions for the wedge of CD in the Mini Spec: the primary function is to act as a diffraction grating, i.e. to split incoming light into its component wavelengths (Ivanjek et al., 2020). Since the CD has similar capabilities to a costly transmission/diffraction grating in the visual spectrum it can be used as an inexpensive replacement (Wakabayashi et al., 1998). The secondary function of the CD is to reflect these dispersed wavelengths so they can be viewed through the eyehole. In a similar fashion to the slit, students' understanding of the purpose of the wedge of CD was gauged using a fixed response questionnaire item in cycles 1 and 2, both pre- and post-lab. The item was based on a question from the SpecUP designed by Forbes (2016), see below. Again, the questionnaire item included "I am not sure" as the first option. Option A from the SpecUP questionnaire was replaced by option B, which is more correct for the reasons stated above. The number of student responses are given below in Table 7 and this is translated into a graphical presentation of percentages in Figure 16.

SpecUP Educational Spectrophotometer Questionnaire: A diffraction grating in a spectrophotometer:

- **A. Reflects the light from the source**
- **B.** Focuses the light from the source
- **C.** Provides the wavelength of light required
- **D.** Absorbs the unwanted wavelengths of light
- **E.** None of the above

Table 7. Number of student questionnaire responses to, "The purpose of the wedge of CD is to:"

	Cycle 1: Pre-lab	Cycle 1: Post-lab	Cycle 2: Pre-lab	Cycle 2: Post-lab
A. I am not sure	54	10	60	20
B. Split light from the source	**242**	**223**	**211**	**187**
C. Focus the light from the source	100	73	101	77
D. Give the Mini Spec the correct shape	21	12	15	11
E. Absorb specific wavelengths of light	15	29	27	26
F. None of the above	11	11	11	11
Total	443	358	425	332

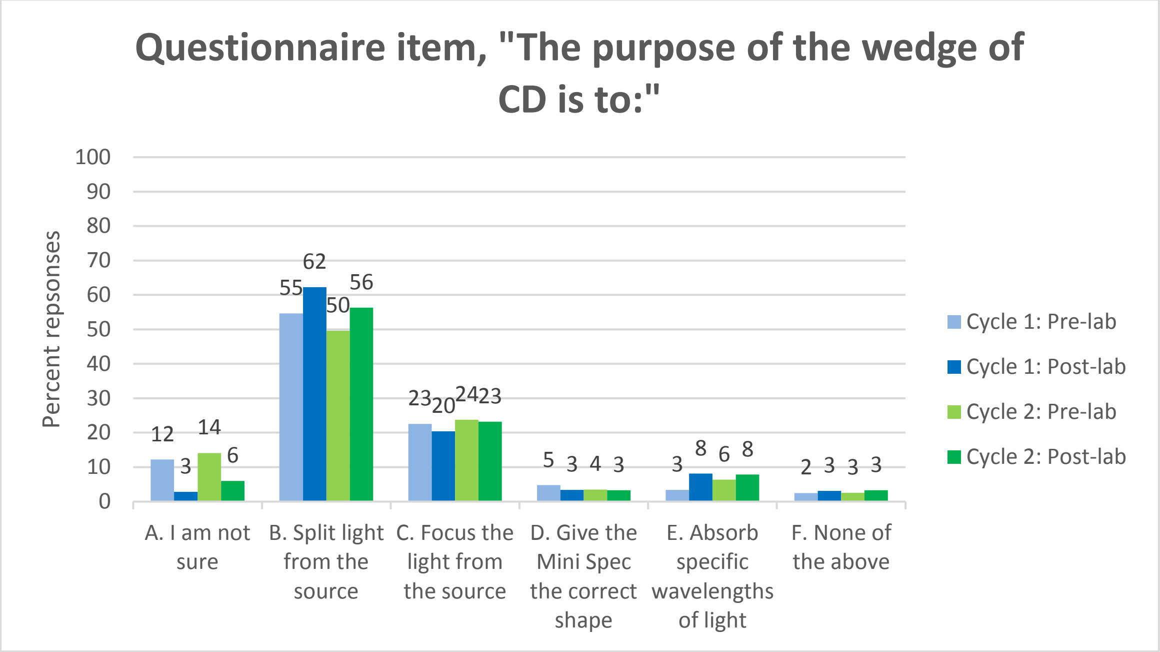


Figure 16. Graph of the percent of student responses to "The purpose of the wedge of CD is to:"

The understanding of the purpose of the wedge of CD is low in the pre-lab in both cycles 1 and 2 and does not appear to improve much in either post-lab cycle (see Figure 16). The selection of the principle distractor, option C, may reflect a lack of understanding of the everyday word "focus" used as a scientific term in optics.

Therefore, in cycle 3 the same design decision was implemented: with the removal of the questionnaire item and replacement with an open-ended question in the report sheet, ***"What is the purpose of the piece of CD in your Mini Spec?"*** so that students would be able to interact with their colleagues, demonstrators and academic staff to discuss the purpose of the CD. As explained in Chapter 3, cycle 3 is small in term of sample size, n=9 where cycles 1, 2 and 5 had many participants. Table 8 shows similar findings for cycle 3 to those from cycles 1 and 2, in that only approximately half of the students' understanding of the purpose of the CD was correct.

Table 8. Coding of students' written report sheet responses on the purpose of the wedge of CD for cycle 3 (*n*=9).

Code	Representative written responses	Frequency (*n*)
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.	"It shows the spectrum of lights for different types of lights" P33 "The disc reflects light and **emits** colour" P36	4

Code	Representative written responses	Frequency (*n*)
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 in physics may have angles other than 180^{o}.	"To reflect the colour of the spectrum" P41	1
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.	"The piece of CD separates light into its different wavelengths, therefore different colours will be observed" P38 "It separates light into its components, and its different wavelengths and frequencies" P34	4

The introduction of this question into the report sheet for the wedge of CD was not as successful as it had been for the slit. However, the question designed for the slit in cycle 3 had a guided exploratory element "***What would happen if the slit was too large? Or too small?"***, which cannot be duplicated for the CD. Upon reflection, a guiding cognitive element was added to the question to assist students in creating meaning for the purpose of the wedge of CD. For cycles 4 and 5, the design decision was made to rephrase the question to prime the perception filter and stimulate feedback from the long-term memory, ***"How is the piece of CD in your mini spec similar to a prism?"*** The phrasing of this question links the current Mini Spec laboratory experiment to high school demonstrations and familiar illustrations of prisms splitting white light into colours of the rainbow.

The coding of responses from cycles 4 and 5 was thought-provoking as many students used the word ***refracts*** in place of ***diffracts***. Refraction is defined as the bending of light in different media e.g. 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, "The CD refracts the white light into seven different colours" (P29), the meaning coincides with diffracts in this scenario, therefore was also coded as 'Good understanding', see Table 9.

Table 9. Coding of students' written responses on the purpose of the wedge of CD for cycle 4 and 5 (*n* = 52).

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 in physics may have angles other than 180^o.	"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 explanation given.	"It diffracts and splits light into it's component colours" P27 "It refracts the light in the same way that a prism does by separating the light into it's different colours" P42	34

*Several responses were not coded due to missing data or the quality of the photocopied handwritten report sheets

The rephrasing of the question, ***"How is the piece of CD in your mini spec similar to a prism?"*** could be viewed as negative as it may have led to students conflating the meaning of the words refract and diffract. However, at this level, the learning outcome was to understand that the purpose of the wedge of CD was to split the incoming light and such discernment was not a priority.

The Mini Spec experiment was designed to provide a macroscopic exposure for students to the topic of emission lines and spectroscopy, as the symbolic and submicroscopic or theoretical components were taught formally. Whether dealing with the chemistry triplet or triangle (Johnstone, 1991), a complex structure (Talanquer, 2011) or a continuum (Taber, 2013), the binding thread that enables and displays learning on different levels is language. As noted by Rees et al. (2019), language may be a barrier for students' understanding or communication thereof. In analysing written and recorded student reasoning from cycle 3 onwards in the open responses, the words reflect, refract and diffract were used by students without much distinction. There may be several reasons for this:

1. The words look similar in appearance and sound similar in pronunciation (Oyoo, 2017).
2. The words come from the same "word families" i.e. optics (Rees et al., 2018a).
3. The meaning of the words is not well understood, students lack appropriate prior knowledge to distinguish between (or apply) the terms of reflection, refraction and diffraction. This corresponds with "language fluency" referred to by (Rees et al., 2019).

The review by Rees et al. (2019) details pedagogical strategies focusing on language and literacy to overcome barriers to understanding. In acknowledging this and going back to the framework of this study, cognitive load is reduced when students have access to well-connected schema in their long-term memories. 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-lab activity that highlights the differences and similarities in these words perhaps with the use of an animation or video.

4.2.3 Emission spectra: The formation of spectral lines

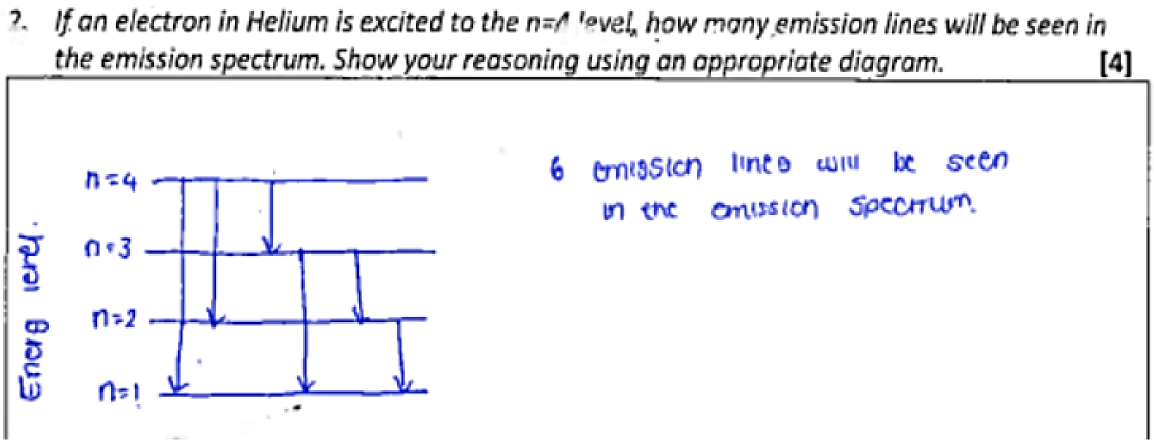
Students' understanding of the mechanism of the formation of spectral lines is a key learning outcome in undergraduate chemistry or physics courses that include spectroscopy in the curriculum (). In fact, according to Ivanjek et al. (2015a), if students understand the concept of the formation of spectral lines, it is likely that they have grasped many other spectroscopic concepts. That is, spectral line formation is a threshold concept in that “it exposes the hidden interrelatedness of phenomena” (Cousins, 2006; Meyer and Land, 2006). For these reasons, the pre- and post-lab activities of the Mini Spec laboratory experiment were designed to strengthen students' understanding of the formation of spectral lines, which had been taught during lectures.

The laboratory report sheet was structured across all cycles (1-5) to include a pre-lab activity. Pre-lab 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-lab activity required students to return to the lecture content to answer the following question, “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.” This activity had to be completed before students were allowed to enter the lab (see Report Sheets Appendices C and D).

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 from cycle 3 to cycle 5 showed that the students correctly drew sub-microscopic models of the principle energy levels in the atom along with the possible downwards transitions that would result in six unique emission lines (see Figure 17 and Figure 18). However, many students omitted the electron itself in their drawings; this was initially thought to be an oversight along with the omission of photons from their drawings. Unfortunately, report sheets from cycles 1 and 2 were no longer available for coding as the pertinence of this data was not anticipated, however, it can be assumed that the findings would be similar to the later cycles as the student cohorts all received the same lecture content.

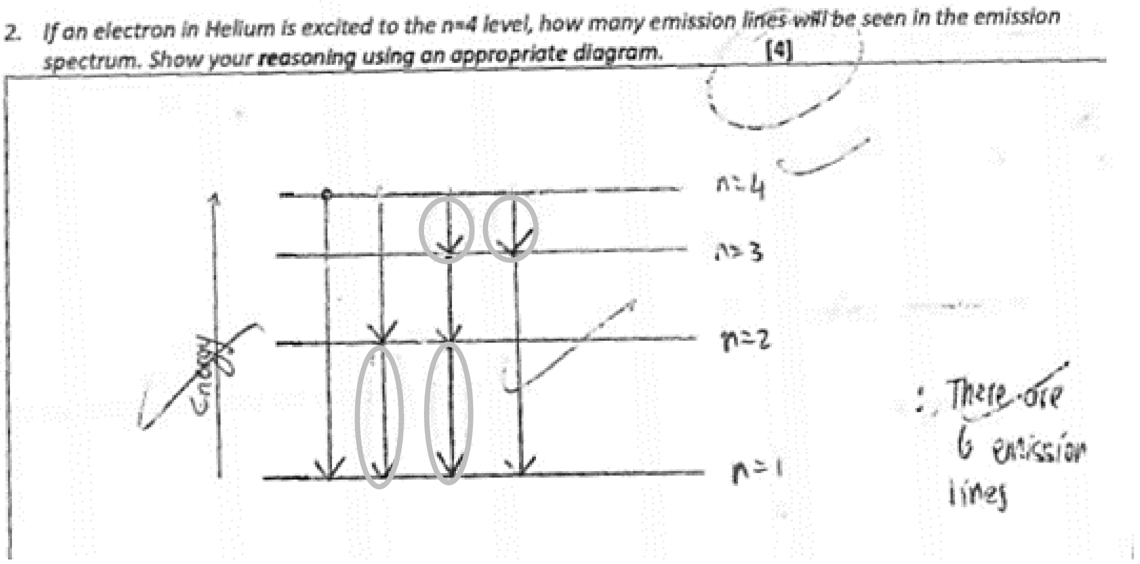
Figure 17. A student's response to the pre-lab activity (Cycle 3, P41)



2. *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 18. A student's response to the pre-lab activity (Cycle 4, P51). Here the student acknowledged 8 possible transitions that would still result in only 6 emission lines.



2. *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

To further probe students understanding of the process of spectral line formation, and track any growth in understanding from the pre-lab to the post-lab activity, a single fixed MCQ item was used as both the pre- and post-lab questionnaire from cycle 3 onwards, accompanied by an open response item which provided students the opportunity to motivate for their answers (see item below and full pre-lab and post-lab questionnaire in Appendices G and H). This item was chosen for this study as it represents a cumulative assessment tool proposed by Ivanjek, et al. (2015a) after a large-scale study that sought to identify student difficulties with atomic emission spectra over four years with approximately 1000 participants. The design of the item was purposeful in highlighting conceptual difficulties around spectral line formation by including the inter-related concepts of spectral lines, photon energies, and energy levels in the options given (Ivanjek et al., 2015a). This rich, yet economical, fixed response item was fully utilised in this study, not just as a once-off question but as the individual pre- and post-lab benchmark questionnaire *and* a discussion point that was fully interrogated through guiding scaffolding in the collaborative post-lab activity.

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

(Ivanjek et al., 2015a, pp. 89)

In returning to this study, it should be noted that the pre-lab activity was completed before students entered the lab. Then, upon entering the lab, students from cycle 3, 4 and 5 were given the opportunity to fill in the pre-lab questionnaire that assessed students understanding of the formation of spectral lines. After completing the experiment, students were again given the opportunity to complete a post-lab questionnaire that posed the identical question. Students were also given space to motivate for their answer in the pre-lab and post-lab questionnaires prompted by the following: “Compare your current choice to your original choice. Motivate why you either kept or changed your answer.”

When classifying students’ answers, the following four quadrant descriptor system was used: CC for students who were able to select the correct answer in both the pre- and post-lab questionnaire, IC for those who were incorrect in the pre-lab but corrected their answers post-lab, II for those students who remained 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-lab questionnaire. Students' responses from cycles 3 and 4 are grouped below as the questionnaire item used was the same (see Table 10).

Table 10. Students' responses from cycle 3 and 4 to the questionnaire item, "Spectral lines are formed when"

		Post-lab	
		% Correct (n)	% Incorrect (n)
Pre-lab	% Correct (n)	**CC** 54% (14)	**CI** 8% (2)
	% Incorrect (n)	**IC** 19% (5)	**II** 19% (5)

The five IC students exhibited partial understanding in the pre-lab questionnaire by acknowledging that transitions between levels result in emissions but selected the photons as those transitioning (option C), not the electrons (option B). This finding highlights the relevance of the comment made after analysis of the pre-lab activity: most students did not show either the photon of the electron in their drawings. However in the open item of the post-lab questionnaire, all five IC students from cycle 3 and 4 acknowledged that they realised that it was the *electron* that was transitioning: "When the electron moves between energy levels, light is observed" (P48) and "My answer changed because I realised when an electron jumps a certain amount of energy levels down, it releases energy…" (P57). This data suggests students were uncertain of the distinction in the role of the electron and photon in the formation of spectral lines prior to completing the prac, and that students benefitted from engaging with peers and staff.

Students from cycles 3 and 4 participated in a recorded collaborative post-lab activity after completing the post-lab questionnaire individually. Listening to the recorded collaborate sessions in trying to clarify the origin of the students' uncertainty between protons and electrons, the researcher realised that another factor had also come into play that added to students' difficulties in understanding electron transitions. Vignette 4 shows the discussion around the simple, non-technical terms "jumps" and "falls" or "drops". Similar discussions happened in half of the eight collaborative recordings: there was a pre-occupation with the term "jumps" for ESL students that altered sense-making around the concept of electron transitions and photon emissions.

Vignette 4. Excerpt from collaborative discussion, group 1, cycle 3

Female: I'm confused between B and C. For B I understand that if an electron jumps like it is going down between energy levels. Jumps and then falls down between energy levels.
Male: What if it doesn't jump?
Female: But it is going to fall unless there is too much power to eject it. It (the electron) is always going to fall.

Male: *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.*
Female: *But when it jumps it doesn't really emit anything does it?*
Male: *It does emit, some energy will be emitted.*
Female: *Because the energy increases as you go up?*
Male: *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.* *FG1 1:5*

A 'just-in-time' design-decision was made to adjust the wording in questionnaire in cycle 5 so that option B and C would become more similar for ESL students: the word "jumps" was replaced with "drops" (see below).

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

It was gratifying to note that this design-decision resulted in a shift in the proportion of responses from the IC quadrant (cycles 3 and 4) to the CC quadrant in cycle 5. That is, the majority of the students in cycle 5 were able to correctly identify the role of the electron in spectral line formation in both the pre- and post-lab questionnaire. This finding signposts the importance of language and terminology used, even if it may appear as inconsequential. Consistently, the percentage of students with misconceptions on spectral line formation (II quadrant, coded as Poor Understanding) remained the same from cycles 3 and 4 (19%) to cycle 5 (19%) (see Table 10 compared to Table 11).

Table 11. Students' responses from cycle 5 to the questionnaire item, "Spectral lines are formed when".

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

Further analysis of the recorded collaborative activity was used to understand the findings from cycle 5 (Table 11). To ground this analysis, the researcher draws attention to the parallels that exist between the format of the students' experience in this study, i.e. a lecture, laboratory exercise including conceptual questions and collaborative post-lab activity, and Peer Instruction. Peer Instruction relies on student exposure to a concept, student responses to a question on the concept, student discussion of the question whilst trying to convince their peers and the completion of a second round of responses (Crouch & Mazur, 2001). Usually in the case of Peer Instruction, if 30-70% (ideally ~50%) of the students had the correct response before peer discussion, then the largest improvement in learning gains should be seen in the second round of responses (Crouch & Mazur, 2001; Schell & Mazur, 2015). That is, students in this study should fare better in understanding the formation of spectral lines in the collaborative activity as it parallels the discussion and second round of responses in Peer Instruction. However, only 4 of the 8 groups from cycles 3 and 4 selected the correct option for the formation of spectral lines in the post-lab collaborative activity (Table 10); a sharp decline when compare to the individual responses of 19 of 26 students (73%) in cycle 3 and 4 who chose the correct answer in the post-lab questionnaire. Group 8 (cycle 4) is of particular interest as all 4 participants selected the incorrect responses in the pre-lab questionnaire but 3 of the participants selected the correct response in the post-lab questionnaire. However, the participants in group 8 selected the incorrect response again during the collaborative post-lab activity (see Vignette 5). Note that in Vignette 5, the students also discussed the last item of the collaborative activity, “Discuss the four remaining options in Q3. To what extent do you agree with the options given? How could each of the options be changed so that the statement is correct?”, (see Collaborative activity, Appendix I).

Vignette 5. Two excerpts from collaborative discussion, group 8, cycle 4 at 4:45 mins and 13:15 mins

Male 3: Like, when is spectral lines formed? ***(4:54mins)***
Male 2: Hm. According to what we wrote there, we chose B
Male 3: Ja
Male 2: from what I remember
Female: Nooo!
Male 2: Remember the
Female: the wavelength
Male 2: the wavelength
Female: It’s C
Male 2: It’s C?
Male 3: C
Male 2: Ja, C
Male 3: A photon <u>drops</u> between energy levels
Male 1: Oh, ja, C, it <u>drops</u>

Later in the recording, discussing how the statements could be changed so that the answer is correct (13:15 mins)
Female: Next!
Male 1: (reads ***option B,*** *Spectral lines are formed when:)* ***An electron jumps between energy levels in an atom and emits a photon***
Male 2 Remember, we chose C
Male 3 (Rereads softly to himself) Spectral lines are formed when an electron drops between energy levels in an atom and emits a photon
Female Remember we said a photon <u>drops</u> over an electron <u>jumps</u>!
(Long pause, various participants sighing)

Male 2 But B is also correct
Male 3 Leave it, let's go to D
Female (laughs)
Male 2 (Unsatisfied sound)
Male 3 Come back, let's go to D. (students did not return to the discussion of B)

There are many factors that constrain learning gains in a collaborative or Peer Instruction learning environment including group dynamics and task structure and complexity (Crouch & Mazur, 2001; Kirschner et al., 2018). However, for the concept of spectral line formation, language appears to be a significant barrier that amplifies the task complexity and may have led to unproductive collaborative transactions between participants (see vignettes above). Specifically, the use of the non-technical word "jumps" to describe an electron transition re-emerges as problematic when students attempted collective sense-making of spectral line formation. Students were able to overcome this language barrier (19% IC for cycle 3 and 4) from the pre- to the post lab questionnaire, however, evidence from the recorded collaborative activity suggests that this freshly formed insight unravels in the face of doubt in the meaning of the term "jumps" for ESL students. This finding suggests that there may not have been enough time to secure the insight in the students' long-term memory and that efforts must be made to firmly embed new insights before testing them in a collaborative context.

4.2.4 Emission spectra: Classifying spectra

When dealing with visible light sources, the emission spectra are classified as either discrete or continuous. Most artificial light sources like energy saver globes give a discrete spectrum which is always unique to the materials from which they were constructed. 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 (e.g. quantization of energy levels, see 4.2.5). However, even the starting point in non-technical terminology is challenging, especially from a novice ESL perspective.

Discrete is the term frequently used by educators and in learning materials to describe a spectrum consisting only of small or isolated segments of the electromagnetic spectrum i.e. a line spectrum. The term, discrete, poses immediate cognitive load, as it 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 scaffolding the meaning of discrete in a scientific context.

Understanding the characteristics of spectra and the implications of these characteristics in terms of the structure of the atom were required learning outcomes. These were measured in Cycles 1 and 2, using a pre- and post-questionnaire as described previously. The questionnaire item was based on a problem from the prescribed textbook for this course (see below).

Textbook problem: What is the most important observation about the spectrum observed for gaseous hydrogen?

- **A.** Several different colours of light are emitted
- **B. Only certain wavelengths of light are emitted**
- **C.** That any light is emitted at all

The questionnaire item used in the study focussed on an energy saver globe instead of hydrogen gas as the spectrum observed of an energy saver globe in a low-cost laboratory is also discrete and hence indicates quantized energy levels within the materials.

Table 12. Number of student responses to the questionnaire item, "The most important observation of a spectrum from an energy saver globe is that:"

	Cycle 1: Pre-lab	Cycle 1: Post-lab	Cycle 2: Pre-lab	Cycle 2: Post-lab
A. I am not sure	78	20	92	34
B. A full continuous spectrum is seen	116	130	120	154
C. No light is emitted at all, it is all absorbed	24	20	33	25
D. Only certain bands of coloured light are emitted	**117**	**85**	**180**	**119**
Total responses	335	255	425	332

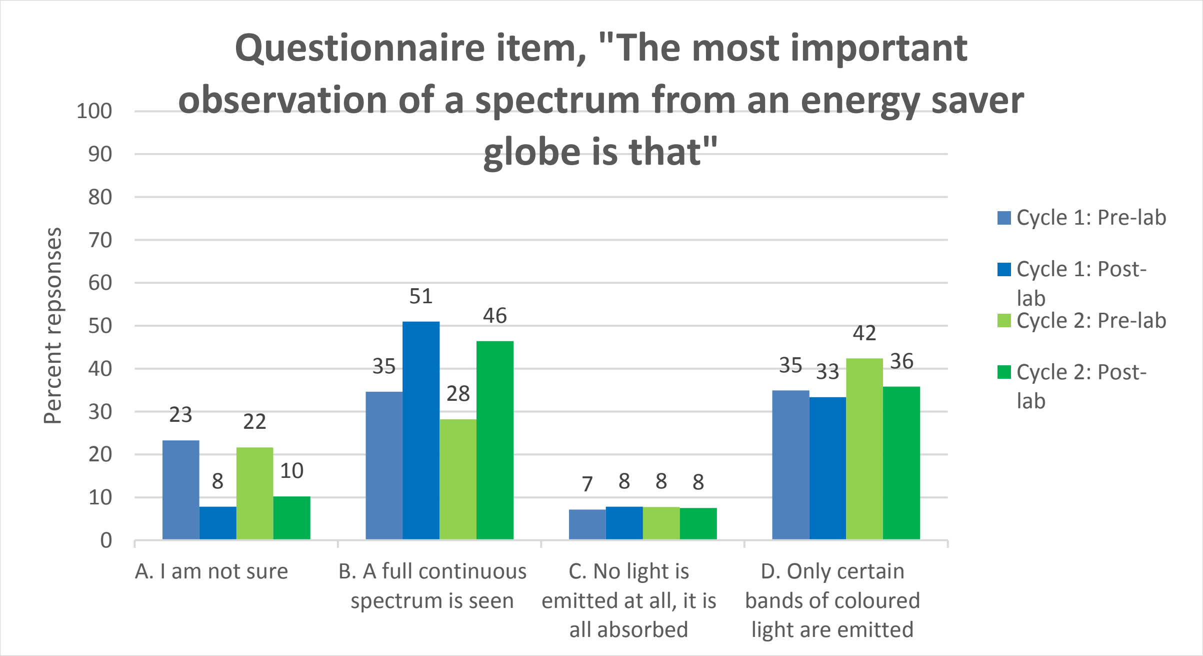


Figure 19. Graph of the percent of student responses to the item “The most important observation of a spectrum from an energy saver globe is that:”

Option B (incorrect) followed by option D (correct) were the most popular selections in Cycle 1 (see Table 12 and Figure 19). However, these options are contrasting in terms of their descriptions of the spectra of an energy saver globe. Initially it was supposed that students were confusing the light sources, therefore labels were added to the light sources in Cycle 2. Students were also made aware of these labels during the pre-prac talk by the laboratory demonstrators. However, the same results were repeated in Cycle 2, indicating that students did not understand the difference between the macroscopic spectroscopic descriptors of discrete and continuous in a real-life context.

In Cycle 3, an open-ended question was added to the student report: *When viewing an artificial light source you see emission lines with your Mini Spec. What is the significance of this finding?* This design decision was made to stimulate the growth of mental schemas for the students: allowing the students an opportunity to engage with their observations and remark on the significance of these observations in their report sheet. Prior to this, students only indicated colours observed in a table.

In the report sheet, most student responses in Cycle 3 focussed on the importance of seeing *different* colours of light from *different* sources (n=6). This was coded as *Nature of the source*, defined as students understanding that different source materials will have unique identifying spectra, in short different spectra will be observed. An example of the coding is “Different elements have different emission lines. Therefore, different artificial lights are made of different elements” (P39). The responses coded as *Nature of the source* showed valid student understanding about the identifying characteristics of unique spectra, however, none of the students’ responses discussed the differences in the *type* of spectra seen.

The key to the final learning outcome of this study (see section 4.2.5) was the correct application of the non-technical terms, discrete and continuous, to the students’ macroscopic laboratory observations. For this reason, a design decision was made to include two additional columns into the table of observations for cycles 4 and 5 (see Appendix D, Report Sheet: Cycles 4 and 5, Q3). The students had to identify the type of spectrum, either discrete or continuous, for each of the four light sources.

The wording of the report sheet question was also changed for cycles 4 and 5 to further scaffold student thinking in terms of the type of spectra observed, i.e. discrete vs. 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 questions were coded as poor, partial and good in their ability to both classify *and* explain their classification of the spectra (see Table 13).

Table 13.Coding of students' written responses on the classification of spectra for cycles 4 and 5 combined (*n*=52).

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 according to their observations, but they do not elaborate on the meaning of the terms or may assign incorrect meaning. This was noted with discrete where students think this means the absence of some colours and do not see discrete as 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 strong 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 were not coded due to missing data or the quality of the photocopied handwritten report sheets

The findings from cycles 4 and 5 showed some improvement when compared to cycles 1 and 2 (see Figure 19) as only 8/46 students exhibited a poor understanding and were not able to classify spectra correctly.

Initially, it was supposed that the 32 students exhibiting partial understanding of spectral line characteristics, i.e. being able to correctly classify spectroscopic types according to their observations, was a positive finding. However, after peer-debriefing and producing the rigorous evaluative rubric, 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 on the table from Q3 in the report sheet, where discrete sources often have spectra without yellow emission lines, for example.

In trying to understand how this concerning and incorrect alternative conception was conceived, it is likely that students did not interact with more knowledgeable tutors, peers, lecturing staff or learning materials like textbooks or internet searches. Students synthesised word-meaning and thus, built concepts for themselves (which was the objective of adding the two columns to the students observational table) however the word-meaning was flawed and does not allow for the next conceptual step: the discovery of quantized energy levels within the atom based on discrete light emissions for the excited electron. This finding brings to light an unexpected design flaw in the scaffolding that was intended to help students build understanding of discrete and continuous spectra.

Students from cycles 4 and 5 participated in post-lab collaborative group discussions. The misconception described above was not known at the time of the collaborative activity, which included the multiple-choice question with the stem: *The most important observation of a spectrum from an energy saver globe is that*. In analysing each of these 15 collaborative group recordings it was found that all groups quickly decided on the correct answer, *(d) Only certain bands of coloured light are emitted,* before moving on to the next question. The speed of their selection implies that students were confident in their answer, i.e. their ability to classify spectra, however, it is likely that the students who had formed the alternate conception of discrete, did not pay attention to the term, bands, in the response provided but only on the fact that certain colours of light that are emitted. Students who already had a strong understanding of the term discrete would not have queried this answer as it is the correct answer, therefore the benefit of collaboration is lost here due to the design of the question and the obscurity or camouflage some students bringing with them in the form of an incorrect alternate conception. This is an unfortunate circumstance in this study in that the collaborative activity may have served to solidify an incorrect misconception in the minds of the students.

4.2.5 Emission spectra: Quantization

In foundational science courses, quantization can refer to the quantization of light, that is the bundles of energy or light referred to as photons by Plank and quanta by Einstein. Quantization can also refer to the quantization of the electronic structure of the atom where electrons are found in allowed states, be it energy levels or more advanced electronic models. In fact, the Bohr model of the hydrogen atom highlights both interpretations of quantization as it is based on emission spectra that show photons emitted as a result of allowed electron transitions within an atom.

The final learning outcome in this study was for students to interpret emission spectra as evidence of the quantized electronic structure of the atom. Arguably this could be both the most complex learning outcome to achieve cognitively, as it depends on most of the previous learning outcomes, and a challenge to measure as it is very difficult to collect data that probe the students' intertwined understanding of emission lines and the structure of the atom. Fortuitously, as first argued by Einstein, and reiterated by Savall-Alemany et al. (2016), the understanding of a quantized atomic model requires an understanding of the probabilistic nature of spectral line intensity. Thus, an understanding of spectral line intensity demonstrates an intertwined understanding of the relationship between spectral line formation and the structure of the atom. Therefore, students' understanding of the varying intensities of spectral lines was used in this study as a proxy for understanding of quantization.

This final learning outcome was only explored from cycle 3 onwards as it relies on the strongly scaffolded understanding of the previous outcomes. The question "For a particular light source, some of the emission lines appear brighter than others. What is the significance of this finding?" was introduced as the final item in the report sheet for cycle 3. This item was similar to the question by Savall-Alemany et al. (2016), "How can you explain that there are some lines with higher intensity than others in a gas spectrum, as you can see in the picture of the helium spectrum?" Three main differences exist between the question used in the study and the question given by Savall-Alemany et al. (2016):

1. The word intensity was replaced with the more common term, brighter
2. Students in this study obtained their own spectroscopic observations using the Mini Spec and were not provided with drawings
3. Gas lamps were not available therefore students used every day light sources instead

In explaining their answer, the student must realise that the question is probing the ***individual*** brightness of certain emission lines from ***one*** artificial light source. We all know that different light sources will have different levels of brightness (lumen outputs) when compared to each other due to the type of material used and the structure of the bulb. But in this case the students should realise that the intensity or brightness of a spectral line within a spectrum is proportional to the likelihood of a particular electron transition occurring or the number of the same transitions occurring at a given time. To best understand this, the reader should refer to Fig. 4 from section 4.2.3, the student shows eight possible electron transitions, where n=4 to n=3 occurs twice and n=2 to n=1 is also repeated twice. All the other transitions only occur once, e.g. n=4 to n=1. This means that of the 6 unique emission lines, there will be two that are brighter or more intense (n=4 to n=3 and n=2 to n=1) than the other four lines. In terms of laboratory observations with the Mini Spec, students should see a similar spectrum to the one given below if two of six transitions were more likely, see Figure 20.

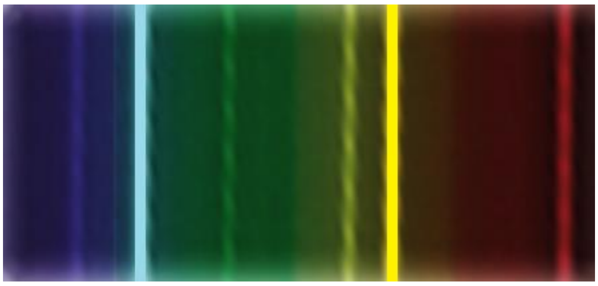


Figure 20. A hypothetical example of a spectrum showing 6 emission lines, two of which appear brighter.

In Figure 20, the dark blue emission line represents a photon of higher energy being emitted than the photons emitted in the light blue line, but the light blue line appears brighter. That is, the photons released do not necessarily have more energy, it is simply that more photons of that particular energy are released. A common misconception is that students do not realise that spectral line intensity is proportional to the number of electron transitions per unit of time but see more intense lines as those having the highest energy (Savall-Alemany et al., 2016).

Eight of the nine students in cycle 3 exhibited poor understanding of spectral line formation according to the relevant section of the evaluative rubric, see Table 14. Coding revealed that the majority of students (n=6) maintained the misconception as described by Savall-Alemany et al. (2016) and the other two students viewed intensity of the lines as a function of the source and its voltage. This disappointing finding from cycle 3 prompted a greater focus on the concept of intensity of spectral lines in the lecture which preceded the laboratory experiment for both cycles 4 and 5.

During the classroom lecture periods that preceded all five cycles, students were asked to draw all possible electron transitions for a hydrogen electron from a certain excited state back to the ground state, this activity is very similar to the pre-lab activity focusing on a helium electron. For cycles 4 and 5 a new design-decision was implemented outside of the laboratory namely, the lecturer prompted students with a follow-on question, asking which transitions would result in the brightest or most intense emission lines? Students were able to vote to answer using a clicker response system. The students were then encouraged to discuss the answers with their peers followed by the lecturer's summary of intensity, in much the same format as Peer Instruction. The impact of this design-decision can be seen in the findings from the report sheets from participants in cycles 4 and 5. Responses from cycles 4 and 5 are combined in Table 14 as the format of instruction they received was the same, see section 3.6.3.

Table 14. Coding of students' written responses on the significance of spectral line intensity for cycle 3 (n = 9) and cycles 4 and 5 combined (n = 52).

Code	Representative written responses	Frequency Cycle 3 (*n*=9)	Frequency Cycle 4 & 5 (*n*=48*)
Intensity, Poor understanding Students give an inappropriate explanation of what spectral line intensity means. Students view intensity as a function of the source. Alternately students equate energy, frequency or wavelength of an emission line to intensity	"Different light sources have different powers, therefore different brightness" P2 "When an e^- jumps from some higher orbit, the energy released in the form of a photon will be greater, and we get a brighter line" RS14 (2:23)	8	27
Intensity, Partial understanding Students see intensity as a function of probability or likelihood. But are uncertain or incorrect as to the probability of **what**? The terms "more of" and "more often" were indicators of this code. Students were not able to communicate that the frequency of electron transitions is the root of intensity. Students may say more of a certain wavelength, frequency or energy. This code shows students developing insight which they cannot fully communicate.	"The brighter colour shows the fact that the *colour* has a higher probability of occurring" P55 "More photons can be emitted thus more energy can be released" P13 "A lot more energy, or a lot less energy at specific wavelengths" P5 "the source produces more of one wavelength than another" P44	0	10
Intensity, Good understanding Students relate the intensity or brightness of a spectral line to the greater likelihood of an e^- transition occurring. Students realize that intensity relates to the **amount** of energy or the **same** photons released **per** unit of time.	"An e^- had made two of the same (equal) transitions from one energy level to the other below it. This doubles the energy emitted, resulting in a brighter emission line" P27 "When there is more than one emission line with the same energy, only one line can be seen but it is brighter or more intense" P26	1	11

*several responses were not coded due to missing data or the quality of the photocopied handwritten report sheets

From Table 14 it can be seen that there was a marked improvement in the proportion of students showing partial and good understanding of spectral line intensity in cycles 4 and 5, however, more than half of the students still showed poor understanding.

In this study, this final learning outcome has not been interrogated using the principles of design-based research to the extent that the previous four learning outcomes have been. However, the analysis of the recorded collaborative group activity provided an opportunity to further probe students' understanding of the term quantization. The second item from the collaborative activity is shown below, where the correct answer, C, contains the word quantized. Note, all groups were able to answer item 1, *The most important observation of a spectrum from an energy saver globe is that,* from the collaborative activity correctly. Item 2 was a follow-on item based on a problem from the prescribed textbook.

2. The most important **<u>conclusion</u>** from spectrum from an **energy saver globe** is that:
   A. I am still not sure
   B. Energy is emitted over a wide range
   C. Emitted energy is discrete or quantized
   D. The wedge of CD absorbs specific wavelengths of light
   E. The slit prevents certain wavelengths of light from entering the mini spec

As explained in section 4.2.4, the characterisation of a spectrum as discrete is a precursor to building the more complex concept of quantization. In this item, the terms were used with a mere "or" between them. Students' discussion of this option gave an additional insight which may also add to the understanding of why students struggle with the concept of quantization. Approximately half of the students who read the question aloud to their group members struggled to pronounce the term quantized. Sometimes the reader was assisted by fellow group members with the incorrect pronunciation. In cycle 3, the term quantized was not discussed at all during the collaborative activity, it was ignored by the participant reading aloud the item.

In

Vignette 6, students only acknowledged the quantization of light but did not link this to the quantized structure of the atom. In

Vignette 7, students conflated the terms, discrete and quantized, and again only discussed quantization in terms of light. Analysis of

Vignette 8 clearly shows that the pair of students could not make the link between discrete or quantized at all. It was only groups 11 and 13 that could articulate the link between discrete emissions and the quantized structure of the atom itself, see

Vignette 9 and 10

Vignette 6. Excerpt from collaborative discussion, group 8, cycle 4

Male 2: (Reads): The most important conclusion from spectrum from an energy saver globe is that:

A. Not sure
B. Energy is emitted over a wide range
***C. Emitted energy is discrete or quantized** (struggles to pronounce, assisted by F1)*
D. The wedge of CD absorbs specific wavelengths of light
E. The slit prevents certain wavelengths of light from entering the mini spec (2:02)

Male 3: Hm, what can you say?
Male 1: Hm, what do you think?
Female: It was discrete
Male 2: Discrete, yea
Male 1: Why is it discrete? Why do you say it's discrete? (2:25)
Female: They were spaces in emitting the…
Male 1: the light?
Male 3: … the light, ja
Male 1: in the emission lines?
Female: Ja
(All talking together)
Male 3: I agree with you, cause, saying that there was
Female: I think that it can be said that only certain bands were emitted
Male 3: Ja, ja (2:52)
Female: It makes sense to say the energy of emission is discrete
All: Agree
Male 2: discrete (repeats the word)
Male 1: or quantized (completes the sentence)
Male 2: So, what is quantized, what is this?
Male 3: Like, ja, I think quantized means maybe there are those quantity of lights, there, the lights
Male 2: Ja, ja…
Male 3: or a packet
Male 2 : or a line

Vignette 7.Excerpt from collaborative discussion, group 17, cycle 5

Female: What is the difference between discrete and quantized?
Male 1: Discrete, it doesn't show all the colours
Female: So quantized is the continuous one?
Male 2: No, it has the same meaning as discrete
Male 3: I chose C because of the first question
Female: Some bands are brighter than the others, so they are quantized. So, the answer is C as a group?
All: Agree

Vignette 8.Excerpt from collaborative discussion, group 18, cycle 5

Female 1: (reads aloud) "The most important conclusion for spectrum from the energy saver globe is that" Yoah. Energy is emitted of a wide range". I don't know about that
Female 2: "Emitted energy is discrete and quantized". (Battles to pronounce, female 1 assists) I don't know what that means we will think about that later because it was discrete, right?
Female 1: Ja

Vignette 9. Excerpt from collaborative discussion, group 11, cycle 5

Female 2: *Ok, I think: emitted energy is discrete or quantized*
Female 1: *Did you see lines between your colours (2:35) if it was discrete?*
Female 2: *Yes, first one was the one that was*
Female 1: *Ja, they had spaces, and then the colours like*
Female 3: *Ja, ja, spaces like – and the continuous one was the one that was blended*
Female 4: *And the reason why I say quantized is because of the wavelength that we were taught in lectures, that it's only certain properties that are shown. So, only certain, hm, colours that we were able to observe, different energies that will make up the energy saver globe.*
Female 3: *Got that!*

Vignette 10. Excerpt from collaborative discussion, group 13, cycle 5

Male 1: Okay, hmm, we are looking to see the emitted energy is discrete or continuous?
Male 2: Quantized? (pronounced correctly)
Male 1: Quantitized (corrects male 2 with incorrect pronunciation)
Male 2: Quantitized? English! (sighs)
Male 1: Quantized or quantitized. Or ja, quantized not quantitized. (corrects himself after saying both words)
Male 3: What is quantized?
Male 1: It means it can only be in a certain energy level like 1,2,3,4,5 and not 1.5 or 2.5…

This finding is not surprising for students on an extended programme, considering that numerous other studies have reported individuals across all levels, be it high school learners, undergraduate students, university teaching assistants and even science teachers themselves, struggle to understand the abstract or complex nature of atomic spectra and quantization (Körhasan & Wang, 2016; Savall-Alemany et al., 2016).

Körhasan and Wang (2016) suggested that barriers to full understanding of atomic spectra may lie in incorrect mental models that omit threshold concepts like electron transitions and photon energy. The findings of this study corroborate the proposal by Körhasan and Wang (2016), that in that most students were able to build a good, but still novice, understanding of electron transitions, see Section 4.2.3, however not all students were able to build a conceptual understanding of the term discrete, which relies on the concepts of electron transitions and photon energies, see section 4.2.4. Understandably, this situation resulted in the concepts of intensity and quantized not forming correctly in the minds of the students. Further evidence of poor understanding of quantization lies in students omitting or ignoring the word quantized in the collaborative activity. We suggest students could not relate the term discrete to quantized, as the meaning they created for the term discrete was not correct, cognitive dissonance resulted in the rejection of the term and a general lack of growth of student understanding of quantization.

As stated previously, the fifth learning outcome was the least supported by design-based research as efforts were first channelled into supporting learning outcomes 1 to 4. However, the findings that were gathered regarding intensity and quantization will help structure future cycles of design-based research. In reflecting on the two aspects of quantization, i.e. quantization of light and the quantized structure of the atom, an opportunity exists to bring these two aspects together through guided questioning. Photons of light are a concept that students have been exposed to since high school and evidence from section 4.2.3 suggests that students understand the mechanism of spectral line formation. Guided questioning may aid the students in the higher order thinking required to create complex understanding of discrete line observations in a lab setting. The task below is suggested and could be incorporated into either the report sheets or collaborative activity.

a. What does quantized mean in terms of light?
b. What does quantized mean when referring to the structure of an atom?
c. How do discrete line spectra relate parts a. and b above?

4.3 Summary

The demands of constructing and using a Mini Spec were seen clearly from cycle 1. The provision of construction references in cycle 2 allowed the students to build the spectroscopes with greater ease, however, understanding of the two basic components of the Mini Spec was still lacking along with the other three more conceptual learning outcomes. Language emerged as a barrier to students' understanding in interpreting written construction instructions but also in the students' gravitation towards optics terminology in the questionnaire. Students appeared to select responses without understanding the meaning of the terms e.g. disperse in Figure 15 or focus in Figure 16. For these reasons the closed-response pre- and post-lab questionnaire from cycles 1 and 2 were replaced by restructuring the lab report sheet, introducing a recorded collaborative activity and replacing the pre- and post-lab questionnaire with one carefully designed item from literature. The refined report sheet allowed students to construct meaning around the desired learning outcomes without the burden of, or attraction to, misunderstood terminology of optics.

This study also aimed to contribute a method to formally assess student learning outcomes in the refined laboratory exercise, as called for by Kovarik et al. (2020). The evaluative rubric was used to code students' mastery of the key learning outcomes from cycles 3 to 5. According to the rubric the students' understanding of the **first** learning outcome, the focusing function of the slit, showed improved understanding from cycle 3 onwards. When describing the diffractive function of the wedge of CD, the **second** learning outcome, the terms reflect, refract and diffract were used by students in their report sheets. Therefore, the evaluative rubric used to code students' understanding made provisions for students' communicated understanding of these terms. Improvement in students' understanding was seen in cycles 4 and 5 when the report sheet item was rephrased to link the purpose of the wedge of CD to that of a prism.

In terms of the **third** learning outcome, a 'just-in-time' design-decision was made to adjust the pre- and post-lab questionnaire wording in cycle 5 so that option B and C would become more similar for ESL students: the word "jumps" was replaced with "drops". This decision yielded extremely useful findings which suggest that students' difficulties in understanding spectral line formation may not only be conceptual: the dissonance created by non-technical terminology may pose the first hurdle for ESL students. It should be noted that these difficulties were amplified in a group environment, not mitigated by it.

The open structure of the refined laboratory report sheet allowed students to express their understanding using terms they felt appropriate. The report sheet was also designed to assist students in building a meaning for words with which they are unfamiliar e.g. discrete and continuous. However, the meaning built by students did not always coincide with the desired meaning. Be that as it may, there was still improvement in understanding the **fourth** learning outcome in later cycles when compared to cycles 1 and 2, where student appeared to guess the meaning of the terms and as such could not classify types of spectra.

The evaluative rubric was used for both the report sheet and collaborative recordings. The findings suggest that the **fifth** learning outcome remained the most poorly understood by the students. That is, most students were not able to relate the quantization of light to the quantized nature of the atom after the completion of the laboratory exercise. In delving into the field of design-based research, the researcher acknowledges that more refinements could be made to the laboratory exercise to improve students' understanding, especially for the two final learning outcomes. Therefore, recommendations are made for future cycles of design-based research, however, implementation thereof is outside of the scope of this study.

As it currently stands, the findings from cycles 4 and 5 show improved understanding in all five principle learning outcomes, to varying degrees. The significance of these findings must not be underestimated, current literature in the field shows students still struggle to understand the basic components of a spectroscope, even when questioning was purposeful in building this knowledge (Ivanjek et al., 2020). Furthermore, these authors point to serious student misconceptions about the nature of the source and the resultant discrete or continuous spectra: many students believed that manipulations of the components of the spectroscope would change the type of spectra and were not able to understand that the type of spectra depended on the nature of the source of incoming light. In contrast to this, the refined Mini Spec laboratory exercise and accompanying evaluative rubric show great promise for understanding barriers and supporting mastery of learning outcomes for novice students in hands-on emission spectroscopy.

CHAPTER 5: The ebb and flow of student understanding

5.1 Introduction

In Chapter 4 the researcher drilled down into each of the five learning outcomes separately. Questionnaire data, report sheet data and collaborative vignettes were used to see the progression of understanding from cycle 1 to 5 within each of the specific learning outcomes. As a reminder, the five learning outcomes, LOs, can be summarised as follows:

LO1:	The slit, as the focusing component
LO2:	The CD, as the diffraction grating
LO3:	Formation of emission lines
LO4:	Classification of spectra
LO5:	Intensity of emission lines (quantization)

This chapter presents only the findings of cycle 5, as cycle 5 represents the fruits of four previous cycles of design-based research which attempted to scaffold student learning of spectroscopy. A cross-section of student understanding of the five learning outcomes in the final cycle of this study should allow for several inferences to be made, see below. However, there are limitations with respect to the validity of these inferences due to small sample numbers for quantitative analysis and the fact that the primary source of data was the student report sheets, which only included one task per learning outcome, as well as the recorded collaborative group activity. In this chapter will be probed as far as possible to determine:

1. The relative difficulty of each of the learning outcomes for a novice student
2. The relationship between achievement of the learning outcomes themselves
3. Learning outcomes that require further support in future, providing focus for future cycles of design-based research

Sections 5.2 and 5.3 complement each other to discuss the cross-section of student sense-making for 29 students in cycle 5. Section 5.2 opens with an overview of the level of students' spectroscopic understanding for each LO, and then goes on to interrogate the flow of individual student understanding based on coding from report sheet data for LO1 to LO2 to LO4 and finally to LO5. In Section 5.3, a cross-section of the learning outcomes achieved in the collaborative activity will be discussed. The design of the collaborative activity centred on LO3, therefore the combination of Section 5.2 and 5.3 should give a more balanced perspective on inferences made.

5.2 Individual cross-section

As described in Chapter 4, students' understanding was coded as poor, partial or good for each of the five learning outcomes. Partial understanding does not represent incomplete or flawed understanding, but rather developing understanding towards mastery of a learning outcome. The researcher acknowledges that there may be weaknesses in the rubric or the application thereof but great lengths were taken to ensure that the coding was not skewed for any particular learning outcome as a rigorous peer-debriefing process informed the refinement and application of the evaluative rubric used for coding, see section 3.8.2. The agreed upon coding was taken as a proxy for the relative difficulty of each of the learning outcomes. In tracking students' individual understanding of each of the learning outcomes for cycle 5, the report sheet data was the focus as it encapsulates learning that occurred during the laboratory experience. It was only for LO3 that the post-lab questionnaire single item response was used, as spectral line formation was not interrogated directly in the report sheet; this data was collected at the end of the practical before students began the collaborative activity.

Figure 21 shows the number of students from cycle 5 that were assigned the coding of poor (red), partial (yellow) and good understanding (green) for each of the five learning outcomes. Using the coding method as a proxy for the relative difficulty of each of the five learning outcomes provided a simple overview. LO1 and LO2 appear to be attainable for novice students in the fifth cycle of design-based research, with understanding the functioning of the slit remaining the more challenging component of the Mini Spec. From Figure 21, LO3 appears to be the most attainable of the learning outcomes after the wording was changed for cycle 5, see section 4.2.3, however, the format of the multiple-choice question provides opportunity for guessing correctly which is no equivalent for self-constructed responses. The distribution of codes for LO3 relative to the other LOs can therefore not be interpreted directly. The depth of student understanding of the formation of emission lines (LO3) will be further explored in Section 5.3. LO4 and LO5 are clearly more difficult for students to master. LO5 appears the most challenging as most students exhibited poor understanding of the significance of spectral line intensity.

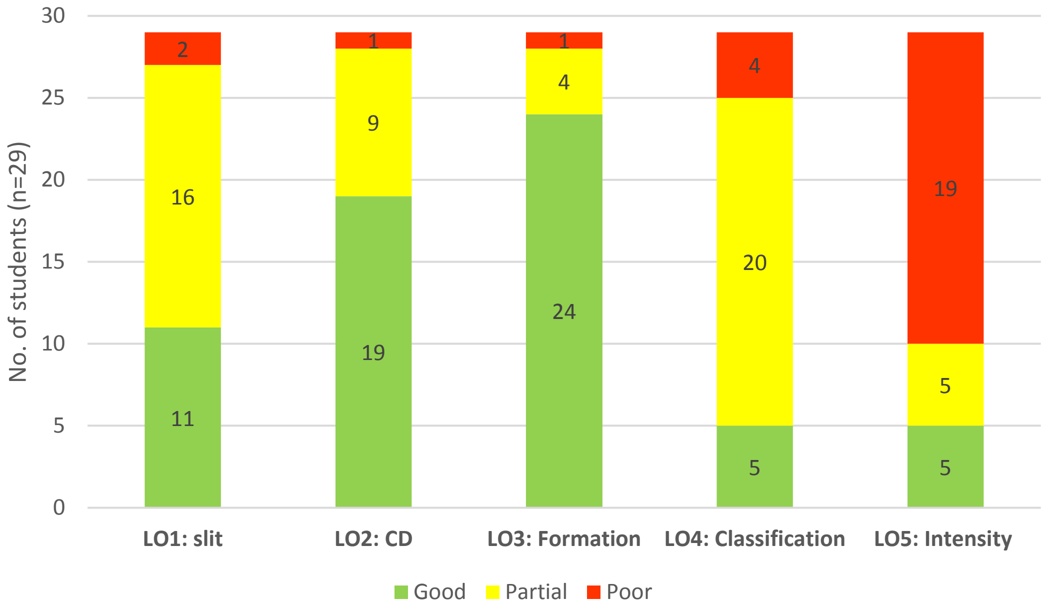


Figure 21. Graph showing the distribution of students in cycle 5 according to coded understanding of the five learning outcomes

Figure 21 represents a simple way to establish the relative difficulty of each of the five learning outcomes compared to one another. It also gives an indication that future cycles of design-based research should focus primarily on LO4 and LO5. However, Figure 21 does not show the flow of student understanding from one learning outcome to the next: Does a student who starts with a good understanding of the components of the Mini Spec necessarily also exhibit good understanding in LO4 and LO5? Is there a relationship in understanding between the learning outcomes? In an attempt to answer these questions, Sankey diagrams were used to show the flow of student understanding. Due to the format of the data for LO3, it was omitted from the following Sankey diagrams. Data programming threads and the website used to generate these figures can be found in Appendix R.

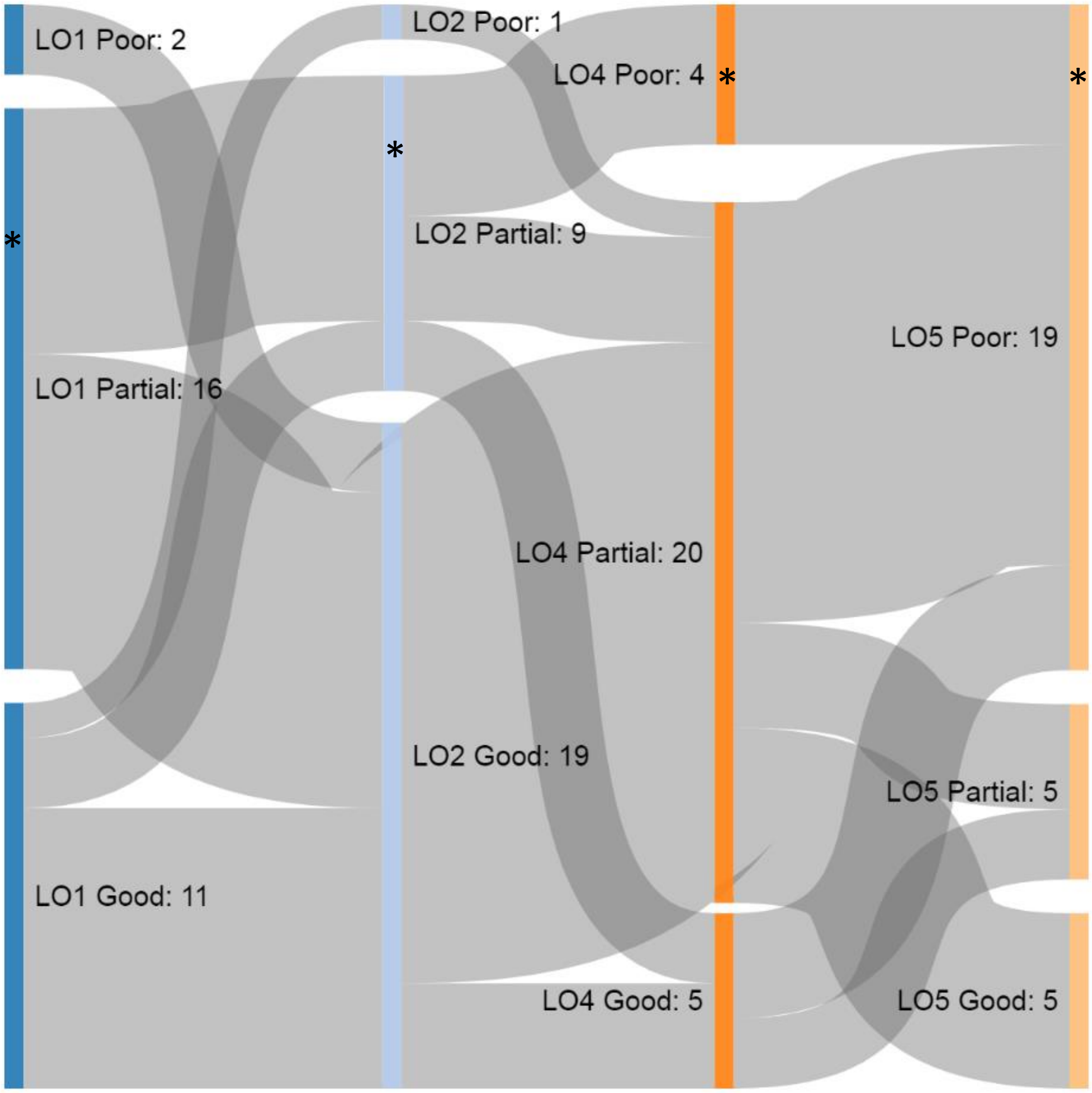


Figure 22. A Sankey diagram showing the total flow throughout cycle 5 of 29 students' competencies between the five learning outcomes.

Briefly, the vertical bars in the Sankey diagrams represent the learning outcomes i.e. **LO1 is dark blue**, LO2 is light blue, **LO4 is orange** and LO5 is peach. Each vertical bar in Figure 22 represents the understanding of 29 students in a particular learning outcome and is divided into sections according to the codes (good, partial & poor) with the height of each section representative of the number of students coded as such. For example, in LO2 (light blue), there is one student coded as having poor understanding, nine students with partial understanding and nineteen students with a good understanding of the diffractive purpose of the wedge of CD. The grey waves reflect the proportion of students that either achieved the same code for an adjacent learning outcome or moved to a different code. For example, the four students that showed poor understanding for LO4 and LO5, showed only partial understanding of the functions of the spectroscope, LO1 and LO2, (see asterisks in Figure 22). Interestingly, no students showed good understanding for all 4 learning outcomes.

Although Figure 22 looks overwhelming at first glance, it clearly shows that there are changes in individual student's understanding of four of the five learning outcomes (there is definite flow in student mastery between learning outcomes). However, there are weaknesses in this format of data representation as it only shows the overall flow and individuals are often impossible trace. In unpacking this data, the first focus was to trace the understanding of those five students who showed good understanding in LO5 (see bottom right of Figure 22). Figure 23 shows that all five students who had a good understanding of LO5 were coded as having partial understanding for LO4 and either a good or partial understanding of the components of the Mini Spec.

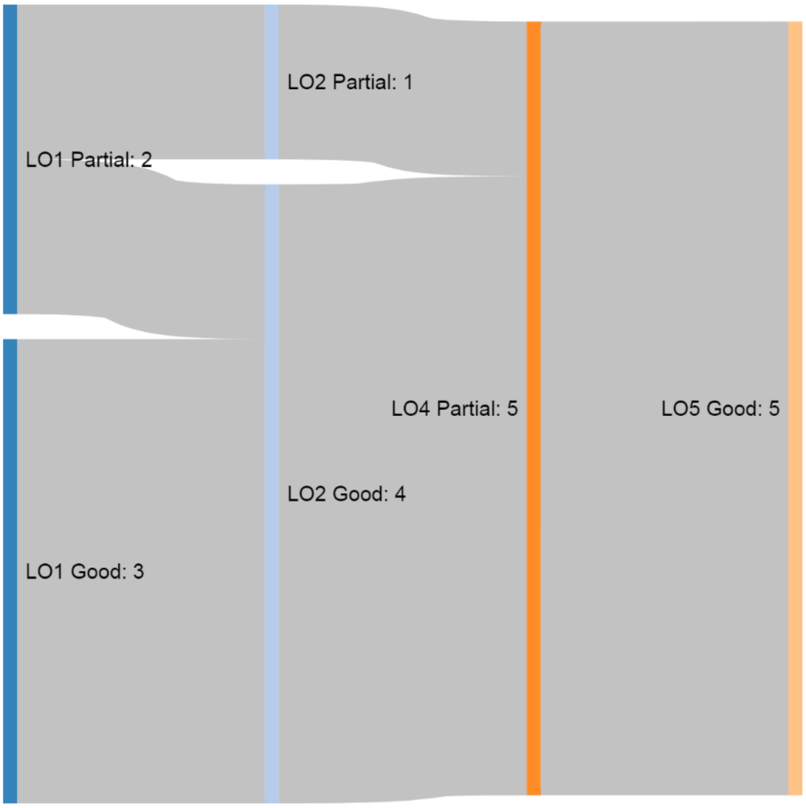


Figure 23. A Sankey diagram showing the flow of 5 students' understanding towards good understanding in LO5.

Before making inferences from Figure 23, it was necessary to check whether students who were successful in communicating their sense-making related to spectral line intensity were not merely top performing students in the course. Students' final mark for the entire semester course was plotted retrospectively against their coded level of understanding in LO5 at the time of the laboratory exercise. From Figure 24, it was clear that student performance overall in the course had no significant correlation with the coded student understanding for LO5 ($R^2 = 0.0763$; $R^2 < 0.3$ is a very weak effect). In addition, students' average coded score for understanding across the report sheets ($\frac{LO1+LO2+LO4+LO5}{4}$) also showed no relationship to their final marks for the course ($R^2 = 0.1081$, not shown in Figure 24). These findings suggest that emission spectroscopy is challenging for all first-year students in the cohort, not just those who may be considered weaker performers. A possible reason for the level playing field is the very limited prior knowledge students bring with them from high school. Emission spectroscopy may be considered a novel concept and as such the inclusion of a laboratory exercise to improve student understanding should have benefits for all students in this context.

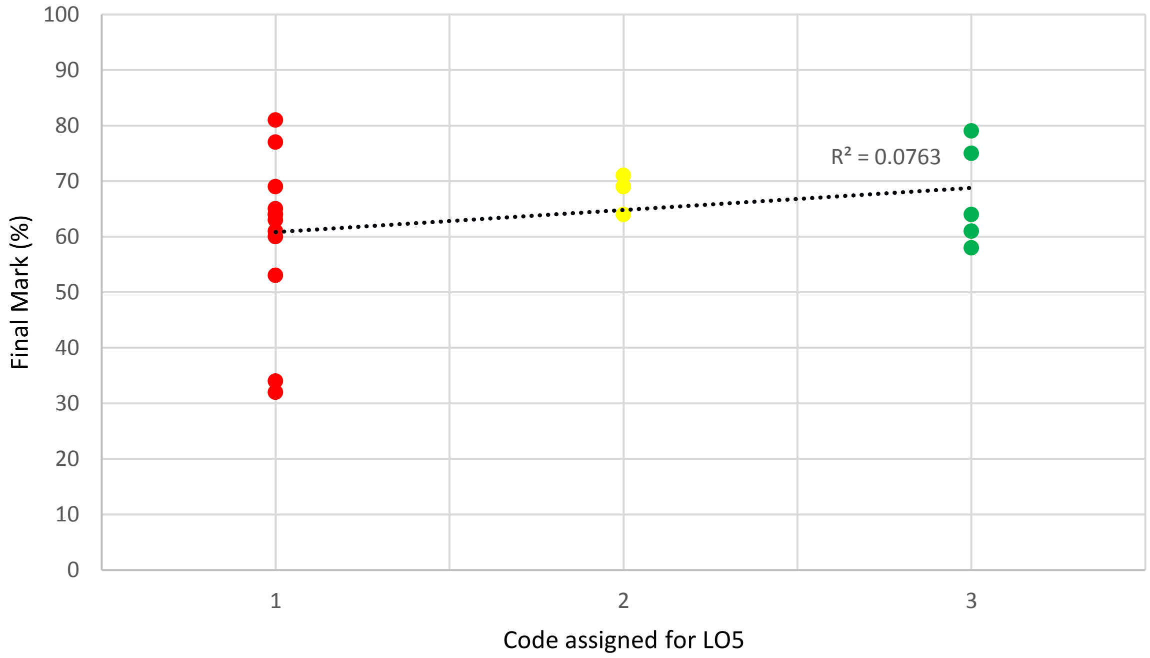


Figure 24. Graph showing the relationship between the student's final mark for the module and their coded understanding for LO5

There are various inferences that can be made based on Figure 23. The first being that these five students who exhibited good understanding for LO5 may have had a good understanding of the terms discrete and continuous, however, were not fully able to communicate this understanding in their answer on the report sheet and as such were coded as having partial understanding for LO4. A second possibility for the partial understanding exhibited in LO4 may lie in the quality of the spectroscopic tool as the Mini Spec is a very simplified spectroscopic tool that was hand-made by the students. These two factors may have led to distortions to the visible spectra observed and hence alternative conceptions arising from the sense-making process, i.e. unclear spectral lines may lead students to lean more heavily on the presence or absence of certain colours in their sense-making of the terms discrete and continuous. A quality control mechanism was in place from cycle 1 to cycle 5 where the lab demonstrators were required to evaluate each Mini Spec before students could begin to make their observations, however, this process is open to human error.

Whether students were unable to communicate their understanding of LO4 or had formed alternate understandings of continuous and discrete, the final inference remains the same: **full** mastery of LO4 is not a prerequisite for good understanding of LO5. In fact, according to Figure 22, the students who exhibited a good understanding of LO4 showed either a poor or partial understanding in LO5. However, a tentative relationship can be seen between LO4 and LO5. Figure 25 shows a cross-section of only those 20 students from cycle 5 who were coded as having a partial understanding of LO4. From Figure 25 the partial understanding formed by 12/20 students flowed into poor understanding in the final learning outcome. This highlights the fact that LO4 requires more attention in future cycles of design-based research despite its relatively favourable outcome compared to LO5.

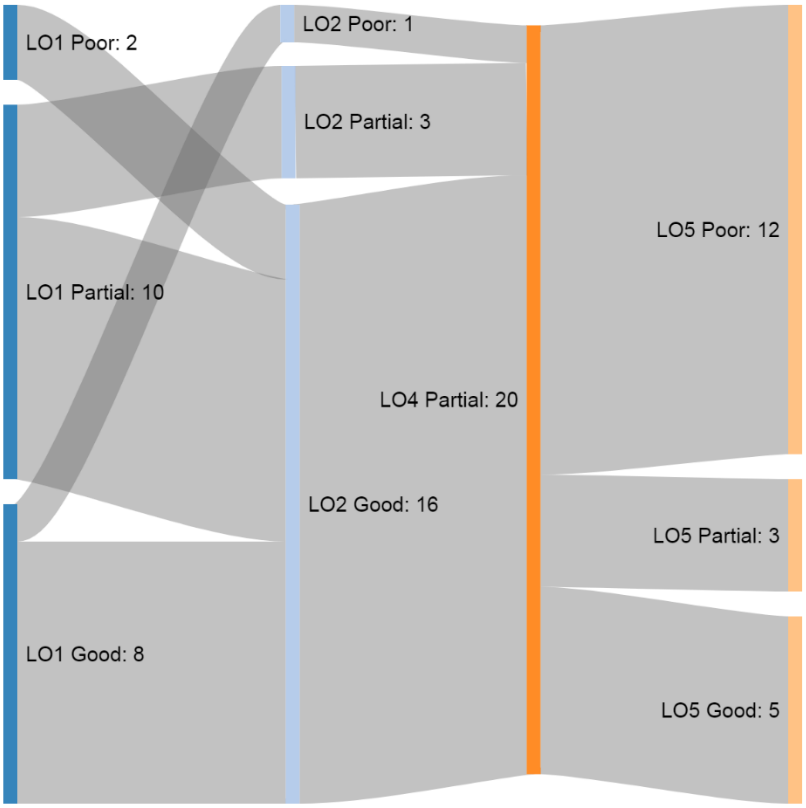


Figure 25. A Sankey diagram showing the flow of 20 students' understanding who were coded as exhibiting partial understanding in LO4

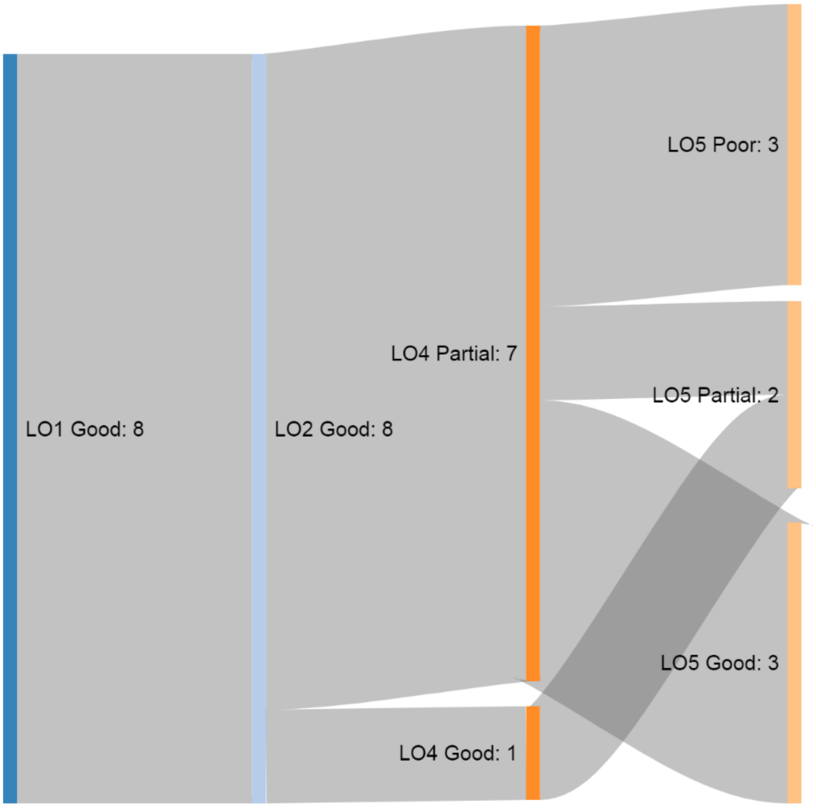


Figure 26. A Sankey diagram showing the flow of competencies for 8 students' who started with a good understanding of both LO1 and LO2.

Initially the researcher asked the question, does a student who starts with a good understanding of the components of the Mini Spec necessarily also exhibit good understanding in LO4 and LO5? Figure 26 shows those students who were coded as having a good understanding of both the principle components of the Mini Spec: the slit and the wedge of CD. From Figure 26 we could see that building a good understanding of the components of the Mini Spec does not necessarily guarantee mastery of LO4 and LO5, but a strong understanding of the components prepares students for at a least a partial understanding of spectroscopic classifications (LO4) and supports a developing understanding of students' explanations of varying line intensity (LO5). This finding is encouraging because it confirms the value of this practical activity for supporting sense-making. Students will revisit the theory of the atomic model after completion of the laboratory exercise when they prepare for tests and the final exam and will be able to draw on their developing understanding of a very abstract and demanding topic.

Summary of findings from the Individual cross-section

The students' overall performance is in chemistry not a predictor of their performance in the laboratory exercise; spectroscopy remains a challenging topic for all. Analysis of the students' report sheets inferred that the most challenging learning outcome was LO5 followed by LO4. Sankey diagrams provided a clearer picture of the patterns in students' understanding in the final cycle, based on the coded report sheets: A good understanding of both components of the Mini Spec, LO1 and LO2, was not a guarantor of student mastery of the more challenging learning outcomes. Conversely, student who did communicate a good understanding of the final learning outcome (LO5) had a minimum of **partial** understanding of the components of the Mini Spec *and* the classification of spectral lines (LO1, LO2 and LO4).

5.3 Collaborative cross-section

In section 5.2, students' understanding of concepts in cycle 5 was tracked according to their individual answers provided on the report sheets. After the laboratory exercise, these same 29 students from cycle 5 agreed to participate voluntarily in a post-laboratory recorded collaborative activity that included four group tasks, see section 3.6.2, 3.6.3 and Appendix I. The collaborative activity was not designed to probe all five of the learning outcomes, it was designed as a reflective post-lab activity for students that allowed the researcher insights into students' understanding of two of the learning outcomes: firstly, students' classification of emission lines, LO4, Tasks 1 and 2. Task 2 did include distractors that attributed incorrect functions to the CD and the slit, and as such, a few of the groups did discuss the functions of these components. Secondly, Tasks 3 and 4 probed students' understanding of the formation of spectral lines (LO3). The collaborative activity in cycle 5 differed from the collaborative activities of cycles 3 and 4 by the small, yet significant, 'just-in-time' change in wording of Tasks 3 and 4 by replacing the word jumps with drops.

In Chapter 4, verbatim excerpts or vignettes were selected from the recorded collaborative activities using the evaluative rubric. These vignettes were used as evidence of the growth of student understanding across cycles 3 to 5 in accordance with the principles of design-based research. In this chapter we present an analysis of the collaborative activities recorded in only cycle 5 through a different lens:

As the groups from cycle 5 worked through the collaborative activity, there were instances of social sense-making and sense-breaking. These instances centred on two or more students discussing concepts relating to the five learning outcomes. The vignettes were re-coded in the final cycle to highlight either positive transactions or negative transactions. A positive transaction was defined as a social transaction that improved the group's understanding of a learning outcome from poor to partial, from partial to good, or even poor to good understanding. Within a positive transaction, alternative or misconceptions may be voiced but overall sense-making must occur. Conversely, a negative transaction was one which weakened the group's understanding of a learning outcome, even if some of what was said was true. These transactions are highlighted using boxes in the vignettes that follow.

This exercise was done to evaluate the overall worth of including a post-lab collaborative activity in its current format, as a tool for guiding and consolidating novice student sense-making, and to aid the researcher in refining the structure of the collaborative activity. The frequency of positive and negative transactions is shown in relation to the learning outcomes in Table 15. For example, group 14's recording lasted 5 minutes and 35 seconds and included a total of 6 social transactions: 3 positive and 1 negative transaction for LO3, 1 positive transaction for LO4, and, 1 negative transaction for LO5.

Table 15. Details of the collaborative activity for cycle 5, including social transactions and duration (N=10 groups)

Group no.	LO1: Slit function	LO2: CD function	LO3: Spectral line formation	LO4: Spectral line classification	LO5: Spectral line intensity	Number of transactions	Duration of recording
4		-1	+2	+1 and -1	-1	6	18’05”
5		-1	+3	+1	-1	6	15’22”
6	+1		+4 and -1	+1 and -1	-1	8	10’47”
12			+2 and -2	+1		5	06’39”
13		+1	+4 and -2	+2		9	21’36”
14			+3 and -1	+1	-1	6	05’35”
15	+1		+4	+1		6	12’45”
16	+1		+1	+1 and -1		4	05’18”
17			+2	+1	+1	4	11’26”
18		-1	+1	+1 and -1		4	05’42”

On average each group in cycle 5 spent just over 11 minutes discussing the collaborative activity (min. 5 mins 18 sec, max. 21 mins 36 sec). In general, the number of social transactions per group appeared to be independent of the duration of the recording. Due to the design of the collaborative activity, it was expected that most of the transactions would centre on LO3 and LO4, and this can be clearly seen in Table 15.

Most of the transactions centring on LO3 were positive, however, negative transactions also occurred which weakened the students’ understanding of spectral line formation. In fact, groups 12 and 13, see red type in Table 15, were the only two groups that decided on the incorrect mechanism of spectral line formation, despite the fact that 2/3 participants from each group selected B, the correct answer, before the collaborative activity. Vignette 11 shows the positive and negative transactions that occurred during group 13’s discussion. The first box highlights the a positive transaction: Male 2 gives a valid mechanism for the downward transition of the electron, even though he states that the electron may have an active role in “holding itself down” (which is not an acceptable concept). The other members of the group accept his reasoning i.e. the downward movement of the electron, and as such this was coded as a positive transaction for LO3.

However, this transaction is immediately followed by another transaction which was led by Male 3. Male 3 correctly highlights that downward transitions release energy and that the energies released will have different wavelengths, however, he suggests that the wavelengths will get larger for transitions closer to the ground state (n = 2 to n = 1) as compared to higher transitions (n = 5 to n = 4). What Male 3 has said has both correct and incorrect elements respectively, but he has also overlooked what is transitioning, using the term "it" instead of electron. By doing so, he and the other participants agree on an incorrect mechanism for spectral line formation, namely option C.

Vignette 11. Excerpt from collaborative discussion, group 13, cycle 5, showing both positive and negative transactions for LO3

Male 3: (Reads Task 3) As a group, which option do you consider 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"

Positive Transaction

Male 1: Which one is the best one?

Male 2: Before we choose the best, in theory we know that as you move up the energy levels the energy increases, right? (all assent) *but as the electron moves down the energy levels it has release energy for it to be able to hold down so that the proton can pull it down. As it emits that energy, get this, the electron not the energy levels are moving down in the energy levels not the other way around.*

Male 3: But in relation to a photon, what is the definition of a photon?

Male 1: A small pocket of energy

Male 3: Yes, as the electron falls down to ground state level, it releases energy.

Male 2: That's very true…

Negative Transaction

Male 3: So, with regards to these options which one?

Male 1: I think its C; spectrum lines are formed when a photon drops between energy levels emitting different wavelengths of light.

Male 2: I won't, I will, agree that it is C, but we have to look at all the different points. Someone might have a different answer…

Male 3: As it moves from the highest energy level to the ground state, for example n=5 to n= 4 to n=3 to n=2 to n=1. So, the wavelengths that are sent are actually longer. So, it releases small energy, best option is C. As a group we agree that the answer is C.

The structure of task 3, taken from Ivanjek, et al. (2015a), and the follow-up task, task 4, provided many opportunities to stimulating group sense-making in spectral line formation. The frequent occurrences of positive transactions indicate the value of the including these tasks in a post-lab activity where students can socially construct and consolidate schema for spectral line formation. As a practitioner, the lack of mastery of LO3 for groups 12 and 13 caused great concern initially, however, according to Kirschner et al. (2018) there will always be costs involved in a collaborative activity due to the load associated with communication, coordination and the demands of the task. These costs should be negated by the benefits of a joint working memory, or the joint sense-making process (Kirschner et al., 2018) and in the case of LO3, this was true for the majority of the groups in cycle 5.

From Table 15 it can been seen that the majority of the transactions around the fourth learning outcome were positive. Group 16, see Vignette 12, provides an example where the initial transaction was coded as negative, even though students arrived at the correct conclusion for task 1. It is true that energy saver globes do not work in the same way as the sun or incandescent bulbs; for the latter two, it is the *heat* created from black body radiation that results in the emission of a continuous electromagnetic spectrum, not the presence or absence of a vacuum. As we know with energy saver and fluorescent globes, very little heat is produced as the electrons are not excited above the threshold frequency, but electrons have enough energy to transition and thus emit photons.

Vignette 12. Excerpt from collaborative discussion, group 16, cycle 5, showing positive and negative transactions for LO4

Male 1: As far as I understand the energy saver globe doesn't work the same way as the Sun or say… what's it called again, the yellow globe?

Male 2: the incandescent globe

Male 1: (continues) the incandescent globe, seeing as it has not a full vacuum around it. So, it does not release all the energy such as the Sun or the incandescent globe. So, the answer should be D

All: Agree, D

Negative Transaction

Male 1: (reads Task 2) "The most important conclusion for spectrum from the energy saver globe is that:

- *A. I'm not sure*
- *B. Energy is emitted over a wide range*
- *C. Emitted energy is discrete or quantized (battles to pronounce)*
- *D. The wedge of CD absorbs a specific wavelength of light*
- *E. The slit prevents certain wavelengths of light from entering the mini spec"*

Male 1: Seeing as some of us got the entire spectrum because of the reflection of light from the energy saver globe, I would rather say that the energy is not emitted over a wide range, it's more discrete so less energy is emitted so less energy is used meaning it's economically better. So, the answer would the answer be C?

Female: Wouldn't it be "The slit prevents certain wavelengths of light from entering the mini spec"?

Male 2: But that wouldn't explain why sunlight has a full spectrum.

Male 1: So C then…

Female: Ja, C.

Male 1: I think I've read enough question someone can read Q3

Positive Transaction

The second transaction in Vignette 12 shows the group building a better understanding of the concept of discrete spectra. Male 1 is incorrect in stating that light sources *reflect* light, instead of *produce* or *emit*, however, his interpretation of the term energy saver indirectly aids Male 2 and Female 1 to construct meaning for discrete spectra and challenge understanding around the purpose of the slit.

Even though the study yielded limited findings for LO1, LO2 and LO5 due to the design of the collaborative activity, there are sufficient transactions to complement the inferences made in section 5.2. Coding of the report sheets for cycle 5 revealed that most students had a partial understanding of the purpose of the slit, LO1. The three positive transactions captured in the voice recordings suggest that the post-lab activity played a role in developing students' sense-making of the purpose of the slit. Vignette 13 shows group 6 negotiating meaning for the purpose of the slit, with two of the participants being more knowledgeable about its function.

Vignette 13. Excerpt from collaborative discussion, group 6, cycle 5, showing a positive transaction for LO1

Male: (reads Task 2): The most important conclusion for spectrum from an energy saver globe is that:

A. Not sure
B. Energy is emitted over a wide range
C. Emitted energy is discrete or quantized
D. The wedge of CD absorbs specific wavelengths of light
E. The slit prevents certain wavelengths of light from entering the mini spec

Female 2: E!

Male & Female 1: No, it can't be E (said in unison)

Female 1: 'Cause it says the slit prevents certain wavelengths

Female 2: Ja. No… It (the slit) doesn't take everything! (incorrectly attempts to liken the purpose of the slit to a filter)

Positive Transaction

Male: *No, no. What the slit does, it focusses light so that light, so that light is not scattered*

Female 2: *Oh (interjects)*

Female 1: *So it does*

Positive Transaction continued

The findings from Section 5.2 indicated that most students demonstrated a good understanding of the diffractive purpose of the wedge of CD in the report sheet, when aided by the guided questioning that likens the function of the CD to a prism. However, LO2 appeared to have more negative transactions than positive in the collaborative activity, see Table 15. Vignette 14 shows a transaction from group 5, which mirrors the transactions from groups 4 and 18. The distractor present in Task 2*, "D. The wedge of CD absorbs specific wavelengths of light"* led the students astray. In all three of these transactions, it was not the collaboration costs but the presence of the distractor that prompted the formation of flawed understanding informed by misinterpreted laboratory observations. The transactions also suggest that students may not fully understand the meaning of the term absorption when applied to spectroscopy.

Vignette 14. Excerpt from collaborative discussion, group 5, cycle 5, showing a negative transaction for LO2

Male: *Then for the CD, the CD wedge, it doesn't absorb every colour because you, some colours were reflected and then gone. So, you're able to observe the colour red, orange and green on the CD wedge.*

Female: *Ja, I can agree with this. Put this the D, the one, the D: the wedge of the CD absorbs specific wavelengths. That's why, like not all of the wavelengths of the colours we actually see, like, instead some of them, meaning most of them were actually absorbed.*

Male: *Ja, most colours, most wavelengths of light were actually absorbed*

Female: *Yes, I do agree. I agree with this one.*

Negative Transaction

Most of the students in cycle 5 were coded as having a poor understanding of LO5 and a partial understanding of LO4 (see section 5.2). The tentative link between these levels of understandings of the LOs that was seen in the Sankey charts, see Figure 23 andFigure 25, was also seen in the analysis of the collaborative activity. In Vignette 15 the participants from group 4 struggled to make sense of the link between the concept of discrete emission lines and the quantized energy released by electron transitions in the atom. Female 3 appears to recall that quantized has a deeper meaning than discrete, however, Female 2 presents the alternate conception of discrete spectra which sways the participants.

A similar transaction occurs in group 6: students cannot make sense of the term quantized as their sense-making for discrete spectra was flawed.

Vignette 15. Excerpt from collaborative discussion, group 4, cycle 5, showing a negative transaction for LO4

Female 2:	*When we say emitted energy is discrete or quantized, it doesn't really make sense to say as if we can count the bands in…, but can we?*
Female 3:	*I feel that quantized is not in that way though, like that's not the meaning, like counting those. It has another meaning. It's just that I can't remember what…*
Female 2:	*I think it says that it's visible, that you can separate the two colours. You don't have any in between colour, maybe a combination of blue and violet, maybe this is what they're referring to?*
Female 3:	*Oh, ja*
Female 1:	*Maybe? (assents)*

Negative Transaction

Groups 5 and 14 re-iterated the common misconception that intensity is indicative of spectral lines with higher energies or frequencies (Savall-Alemany et al., 2016) and as such made no attempts to further interrogate quantization. There was only one positive transaction for LO5 which occurred during group 17's collaborative activity, see Vignette 16. The value of analysing this transaction is that Male 1 obviously developed a flawed concept of discrete spectra during the laboratory exercise and would have passed this misconception to the Female if Male 2 had not intervened. Male 2 highlights the laboratory observations in such a way that it helps Female 1 interpret them correctly, building a developing understanding for the participants evidenced by the joint agreement at the end of this transaction.

Vignette 16. Excerpt from collaborative discussion, group 17, cycle 5, showing a positive transaction

Female 1:	*What is the difference between discrete and quantized?*
Male 1:	*I think discrete it doesn't show all the colours*
Female 1:	*So quantized is the continuous one?*
Male 2:	*No, it has the same meaning as discrete*
Male 3:	*I chose C (Emitted energy is discrete or quantized) because of the first question*
Male 2:	*Remember there is a set of bright bands*
Female 1:	*Ja, some bands are brighter than the others,*
Male 2:	*Ja, quantized!*
Female 1:	*So they are quantized. So, the answer is C as a group?*
All:	*Agree*

Positive Transaction

This final transaction shows a positive step in the right direction for the most challenging LO. The joint understanding was developed towards partial mastery by the presence of a more knowledgeable peer in the group. This notion fits neatly with collaborative Cognitive Load Theory by Kirschner et al. (2018) namely that the prior knowledge that the more expert member brings helps reduce the demands of a task and supports the joint working memory. Upon reflection, this finding suggests possibilities for further cycles utilising a post-lab activity with the purposeful inclusion of a more knowledgeable peer. However, this will be easier said than done as a selecting a first-year student would present its own challenges. Communication costs would be lower as compared to using a more senior demonstrator or member of staff within the collaborative activity.

5.4 Conclusion

The findings in this chapter represent a cross-section of the evolving understanding of students at a specific point in time due to the design-based research approach chosen in this study. The cross-section of cycle 5 not only allowed the researcher to make inferences on the relative difficulty and relationships between the learning outcomes but allowed her to flag areas for future scaffolding. These inferences have also enabled the researcher to reflect on her own understanding of the scaffolding required by students, and how this understanding itself changes with the findings of each cycle.

The complementary individual and group cross-sectional findings from cycle 5 enabled meaningful, yet limited, inferences to be made. From the individual cross-section findings, the relative difficulty of each of the learning outcomes for a novice student could be gauged upfront: LO3 appeared to be the least difficult to understand and LO4 and LO5 appeared the most demanding. The Sankey graphs effectively revealed that students do not necessarily perform consistently in each LO i.e. the LOs are not hierarchical in the traditional sense, however, there are links of varying strengths between achieving the learning outcomes.

The collaborative cross-section added a further layer to the analysis of understanding student difficulties and successes in the final cycle, particularly for LO3. The collaborative activity was valuable in that it confirmed areas (LO4 and LO5) and flagged others (LO2) as foci for future cycles of design-based research. In addition to this, the analysis of the social transactions drew attention to the strengths and limitations of the collaborative activity, in terms of Collaborative Cognitive Load Theory.

CHAPTER 6: Discussion

6.1 Introduction

In this penultimate chapter, the two overarching research questions will be answered. The first research question sought to identify the barriers to student sense-making in emission spectroscopy and the second research question evaluates the extent to which these barriers were reduced over the course of the study.

Sense-making was linked to the efficiency of holding, processing, and organizing information within students working memory. Therefore sense-making was evidenced synchronously in this study by students' manifestation of different levels of understanding in either the answers given on their laboratory report sheet or in their social transactions in the collaborative activity immediately thereafter. These levels of students' understanding of the five relevant learning outcomes were coded as poor, partial and good. If sense-making was impeded, student progress along the continuum from poor to good understanding may not have occurred, thus there existed barriers to the sense-making process.

Language emerged as a major barrier for the students in emission spectroscopy and will be discussed in further detail as it forms a large portion of the significance of this study. This chapter will close with reflection on the use of Cognitive Load Theory to interpret the barriers faced by novice chemistry students.

6.2 Research Question 1

What were the barriers to understanding emission spectroscopy and how were they identified?

Three major barriers emerged to students' understanding of emission spectroscopy from the findings over the five cycles in this study, namely the demands of the task, conceptual difficulties and language. These three major barriers represent groupings of several instances of cognitive difficulty in processing, often evidenced in poor or partial sense-making. The major barriers and the components thereof often only emerged upon careful implementation of cycles of design-based research. Therefore, the researcher does not claim that the barriers presented in this chapter are exhaustive. Likewise, the grouping of the barriers into three major categories was emergent and may have been grouped or categorized differently by another researcher, hence the researcher has attempted to link these emergent barriers to relevant literature wherever possible. Finally, there was overlap between the three major barriers, particularly when it came to language and the intricacies by which language underpinned both the demands of the task and the conceptual difficulties faced by students.

6.2.1 Demands of the task

The first barrier to students' understanding of spectroscopy was the Mini Spec itself. The construction ***time*** it took for students to build the Mini Spec along with their limited understanding of the ***functions*** of the Mini Spec components were categorized as the ***demands of the task***. Parallels exist between the components of this barrier and the analytical framework proposed by (Abrahams & Millar, 2008) to determine the effectiveness of practical work. The construction of the Mini Spec represents Level 1, the physical, practical or "doing" component that was designed by the instructor and carried out by the students. Level 2 encompasses learning or thinking in the laboratory, and, linking the learning to scientific ideas or concepts either during or after the practical (Abrahams & Millar, 2008; Millar, Tiberghien, & Le Maréchal, 2003). In this study, the first two learning outcomes required students to understand the functions of the components of the Mini Spec and their links to concepts in spectroscopy, e.g. focusing and diffraction, and use of Mini Spec to gather data.

The first component, or level, of the demands of the task barrier was apparent from cycle 1; staff observed that students took longer than expected to interpret written instructions and construct their individual Mini Specs using the templates provided. In cycle 2, two large groups of students were evaluated: students who were only provided with the original written instructions (control group, n = 214) and those who were supplied with supplementary construction references to assist them with building their Mini Specs (experimental group, n = 194). The differences between the cycles can be seen between Figure 27 and Figure 28 where additional visual information in the form of construction references were supplied in a similar fashion to the incorporation of visuals by Dechsri, Jones and Heikkinen (1997).

Significantly poorer student performance in the lab report sheet was evidenced for the control group ($t(405) = 3.98$, $p = 0.0005$, Cohen $d = 0.4$) and coincided with the statistically significantly higher construction times required by the control group, who only had written instructions to interpret to guide them in building their Mini Specs ($t(406) = 2.76$, $p = 0.003$, Cohen $d = 0.4$). Increased construction time and poor performance were linked to cognitive overload arising from the demands of interpreting the written construction instructions. A full report of these results was published (Mundy & Potgieter, 2020) and is attached as Appendix A.

Procedure:

1. Carefully cut out the ***slit (a-b)*** and the ***rectangular eyehole (g-h)*** first**,** ask for assistance if required. Do not change the dimensions of the ***slit*** and the ***rectangular eyehole.*** TIP: Practice cutting with your ruler and opened scissors on a piece of cardboard that will not be part of the final mini spec.
2. Cut the provided template out. Cut along the solid lines. Do not cut along any dotted lines. Do not cut the area marked for the CD.
3. Glue the CD piece in place, make sure the iridescent shiny side of the CD wedge is exposed. Take care not to get glue or fingerprints on the shiny side of the CD.
4. Fold along the dotted lines.
5. Complete the Mini spec by folding it into a little box. Glue the edges closed (a to a, b to b, etc.) so that they don't leak light, but do not cover the slit. Glue flaps in alphabetical order. Unlabelled flaps need not be glued.
6. Look into the ***rectangular eyehole*** and aim the ***slit*** at the overhead fluorescent lights in the lab. You may need to tilt the spectroscope to view all the bands.

7. Repeat step 6 with the other sources of light provided.

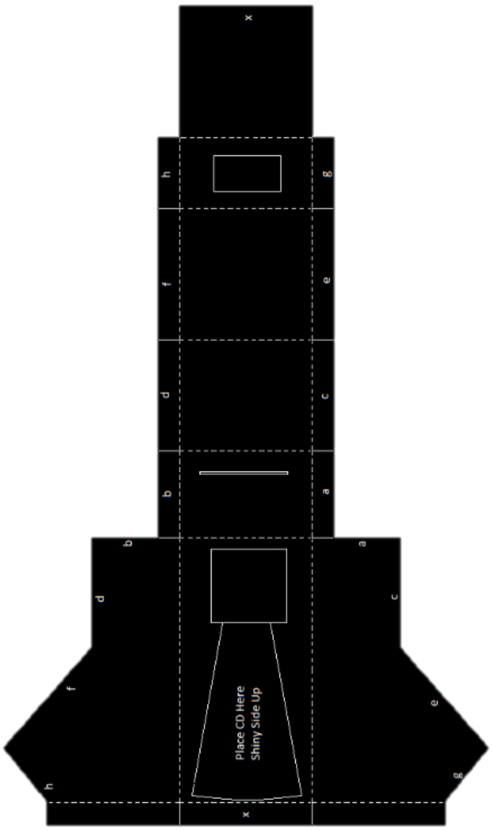


Figure 27. Instructions and template provided to control group in cycle 2

Procedure:

1. Carefully cut out the ***slit (a-b)*** and the ***rectangular eyehole (g-h)*** first**,** ask for assistance if required. Do not change the dimensions of the ***slit*** and the ***rectangular eyehole.*** TIP: Practice cutting with your ruler and opened scissors on a piece of cardboard that will not be part of the final mini spec.
2. Cut the provided template out. Cut along the solid lines. Do not cut along any dotted lines. Do not cut the area marked for the CD.
3. Glue the CD piece in place, make sure the iridescent shiny side of the CD wedge is exposed. Take care not to get glue or fingerprints on the shiny side of the CD.
4. Fold along the dotted lines.
5. Complete the Mini spec by folding it into a little box. Glue the edges closed (a to a, b to b, etc.) so that they don't leak light, but do not cover the slit. Glue flaps in alphabetical order. Unlabelled flaps need not be glued.
6. Look into the ***rectangular eyehole*** and aim the ***slit*** at the overhead fluorescent lights in the lab. You may need to tilt the spectroscope to view all the bands.

7. Repeat step 6 with the other sources of light provided.

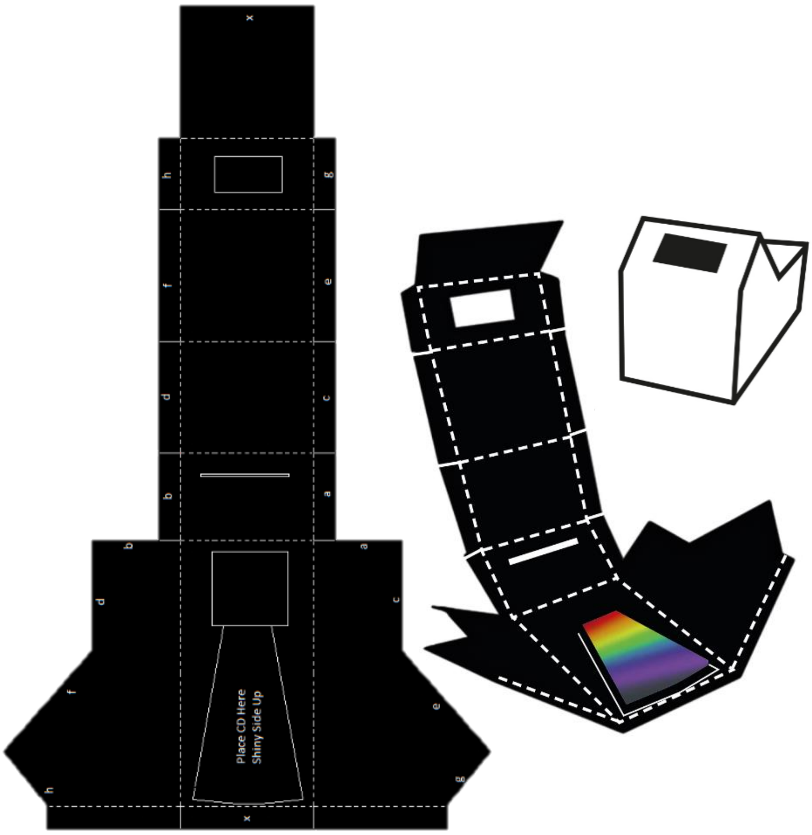


Figure 28. The same instructions and template supplemented with construction references in two stages of completion for the experimental group in cycle 2

From cycle 2 onwards the demands of task also included understanding the function of the Mini Spec components, i.e. the slit for focusing incoming light and the wedge of CD as a diffraction grating, as understanding these standard components is prerequisite for understanding the basic functioning of spectroscopic instruments. In cycles 1 and 2, students completed a pre- and post-lab questionnaire which included items that probed students' understanding of the function of the slit and CD. When the pre- and the post-lab data was analyzed, it was clear that students did not show gains in their understanding the functioning of the two primary spectroscopic components after using the Mini Spec and completing the laboratory exercise. That is, by *doing* the practical, students did not engage with the *ideas* linked to the components of the Mini Spec. This resonates with the fact that doing does not give way naturally to thinking and ideas, the psychomotor laboratory task should be deliberately scaffolded to prompt cognitive processing (Abrahams & Millar, 2008).

In further cycles of design-based research the laboratory exercise was refined to include guiding questions on the purposes of these components if the Mini Spec (see Sections 4.2.1 and 4.2.2). The efforts in this study compliment a set of two tasks recently published by Ivanjek et al. (2020) in which students' understanding of line spectra formation was explored through the use of questions probing the set-up of the spectroscopic components of a common diffraction experiment.

When analyzing students' report sheet responses on the purpose of the slit, the majority of students from cycles 3 to 5 exhibited a developing or partial understanding in that they viewed the slit only as an entry point for the light into the Mini Spec but did not understand its role of focusing the incoming light. Students' understanding of the purpose of the wedge of CD remained poor for cycles 1 to 3, until the report sheet question was redesigned to liken the wedge of CD to a prism. However, students still experienced difficulties in utilizing appropriate terminology to describe the function of the slit, for example, some students used the terms 'defract' and reflect instead of more appropriate terms like refract and diffract.

6.2.2 Conceptual difficulties

The most obvious barrier to spectroscopic understanding was the intrinsically difficult nature of spectroscopic concepts and topics for teaching and learning. In this study LO3, LO4 and LO5 dealt with the formation, characterization on interpretation of spectra, however, progress towards achieving these core learning outcomes was obstructed by several known ***conceptual difficulties***. Conceptual difficulties are known to include concepts of electronic transitions and photon energy (Körhasan & Wang, 2016), discrete spectra (Ivanjek et al., 2015a, 2020), and the quantum model which acknowledges the relationship between the quantization of energy and the atomic structure (Savall-Alemany et al., 2016).

In this study, most students were able to graphically represent the formation of emission lines in the report sheet, however, many students omitted either the electron, the photons or both. This was initially interpreted as an oversight, however, in cycles 3 and 4 it emerged that students did not really pay attention to the threshold concepts of electron transitions and photon energy in the collaborative exercise (see Section 4.2.3) but rather focused on the ***directionality*** of the transition as a downwards motion. Once the debate between jumping and dropping electron transitions was removed for cycle 5 the majority of students could select the correct multiple-choice answer to the stem, **Spectral lines are formed when**. Students' post-lab collaborative discussions showed many instances of increased joint sense-making regarding the formation of spectral lines, however, some interactions were negative despite addressing language barrier (replacing "jumps" with "drops" in cycle 5), again indicating a lack of knowledge about whether electrons or photons are transitioning and what is emitted.

The pre- and post-lab questionnaire findings from cycles 1 and 2 indicated that students did not understand the difference between the macroscopic spectroscopic descriptors of discrete and continuous in a real-life context. Scaffolding incorporated in report sheet for cycle 4 and 5 resulted in most students forming an undesired alternate conception of discrete, as the absence of some colours. The concept of discrete is a steppingstone to understanding spectral line intensity which was used in this study as a proxy for understanding quantization of the atom. The majority of the students could not explain intensity in their report sheets and defaulted to the common misconception that a brighter line represents energy with a higher frequency. In some instances, this misconception was also aired in the collaborative activity.

6.2.3 Language barriers

The final barrier uncovered in this study was that of ***language***; this was a substantial barrier as it underpinned large portions of the above mentioned two barriers but also created difficulties in spectroscopic understanding in and of itself. This barrier manifested in different ways throughout the study: a high task demand was evident in the time required for students to read the written construction instructions and build their Mini Specs. In the report sheets, there were clear instances of the incorrect terminology related to optics used by students in attempting to communicate their understanding of the function of the wedge of CD, this links to language through similar sounding words and words from the same word families as described by Rees et al. (2018a).

As eluded to in the previous section, it was found that describing electrons with the animism of 'jumping' between energy levels created difficulties in students' sense-making (Quílez, 2019; Taber & Watts, 1996), i.e. non-technical terminology used to describe electron transitions created barriers to students' understanding as jumping was often interpreted as an upward motion only. The collaborative activity also highlighted students' difficulties in distinguishing between the terms discrete and quantized, the latter term was often mispronounced or ignored during the students' discussions. Language as a barrier will be further explored in section 6.3.3.

6.3 Research Question 2

How were the barriers to student understanding of emission spectroscopy addressed?

Students' level of mastery of the five learning outcomes was discussed in Chapters 4 and 5, with reasoning and reflections for all the design-based decisions taken, along with evidence of progress made in students' understanding. In seeking to answer the second research question more fully, the researcher's interpretation of the barriers faced by novice students through the study will be explained. The researcher made hypotheses based on Cognitive Load Theory (Paas et al., 2003), which is situated within the Information Processing Model (Johnstone 2006, 1997), to *interpret* possible causes for breakdown in students' understanding, and, to *inform* the numerous refinements of the laboratory exercise with the intention of addressing the three primary barriers.

Before continuing with this discussion, the theoretical lens used by the researcher in interpreting learning and learning breakdown can be summarised from Chapter 2 as follows: words and images represent the dual channels for incoming information into the mind of the student. This information, either audio or visual or both, is stored for a short amount of time in the sensory memory. Relevant words and images that are selected by the perception filter then continue to the working memory where they can be held, processed and organised. Three types of cognitive load impact on the efficiency of the working memory: Intrinsic load (the inherent difficulty of concepts), extraneous load (the format of the information as unnecessarily complex, redundant or disparate) and germane load (the connecting mechanisms of schema construction, assimilation and accommodation). Successfully processed information links in one way or another to existing schema allowing the transfer to the long-term memory where it is stored for future recall. This stored information, along with emotions and experiences, guides the perception filter in selecting and rejecting incoming information. Information recalled from the long-term memory into the working memory reduces intrinsic load if it is relevant to the task, i.e. prior knowledge.

The figures that follow in the rest of the chapter provide visual representations of the memory components that form hypothesised pathways for the processing of information and experiences. These hypothesised cognitive pathways were used by the researcher to identify possible origins of learning breakdown and offered guidance to the researcher over the five cycles of design-based research. To answer the second research question, different aspects of the pathways will be highlighted to demonstrate how interventions addressed barriers to understanding or task execution over the five cycles of design-based research.

The use of design-based research was critical in this study as it allowed opportunities between each cycle for the researcher to fully interact with the theoretical lens of this study. In retrospect, the researcher was able to use the findings of each of the previous cycles to interpret the cognitive pathways for the origins of breakdown which contributed to the barriers that students faced. The identified origins of breakdown became the prospective focus of subsequent cycles of design-based research. Redesign was informed by hypotheses based on the theoretical framework, i.e. the researcher used a proposed cognitive pathway to inform refinements to implementation in the next cycle that should address the barriers faced by the students.

6.3.1 Addressing the demands of the task

The demands of the task were the first barrier interpreted using cognitive pathways which informed three separate design-based decisions. As mentioned previously, the processing required to decipher the written instructions, printed words, and to build a Mini Spec put strain on the cognitive capacity of the students, especially for students for whom English is not their first language. This strain was identified as an extraneous load based on the written format of the instructions, see Figure 29, and was evident in cycle 1. In attempting to reduce the extraneous cognitive load, students from cycles 2 to 5 were provided with additional visual information in the form of construction templates in various stages of completion, see Figure 29.

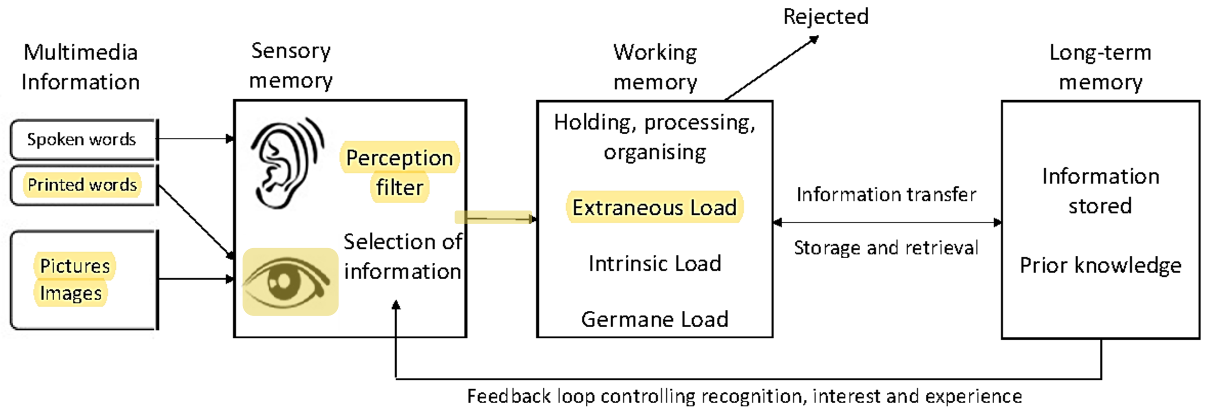


Figure 29. Cognitive pathway targeted to reduce construction time required for the Mini Spec.

According to St Clair-Thompson et al. (2010) the perception filter selects information most important to a task from all the information on offer. The first design-decision, namely additional visual information relating to the construction template, allowed the students' perception filter to consider both sources of incoming visual information and focused the students' attention on the template. The finding of students' improved performance and decreased construction times suggests reduced cognitive load, as visual information may be more easily held in the working memory for ESL students, or alternatively, they could supplement limited understanding of written instructions with visual cues. These findings are similar to those of Dechsri et al. (1997) in which they found that visual information processing was promoted through the integration of pictures or diagrams with text in the laboratory manual, resulting in improved student attitudes and performance. This is much the same as the case in this study where students were motivated to spontaneously share their Mini Specs with their homes and communities (Mundy & Potgieter, 2020).

The demands of the task included students' difficulty in understanding the focusing function of the slit on incoming light. In reflecting on the utility of the previous cognitive pathway, the extraneous load was managed and a portion of the demands of the task barrier was addressed, however, this design-decision did not automatically result in a better understanding the functions of the components of the spectroscope. A different cognitive pathway was proposed to support students' understanding of the slit: one which focused on germane load. To help students build a notion of the focusing function of the slit, the design-decision was made to add a guiding question to the report sheet, "***What is the purpose of the slit in your Mini Spec? What would happen if the slit was too large? Or too small?"*** This guiding question, or scaffolding, prompted students to construct visual information, by physically altering their Mini Specs, or to engage in hypothetical situations regarding the size of the slit in the Mini Spec. The findings from cycle 3 onwards indicated that the scaffolding was successful in creating germane load, enhancing the functioning of the working memory through schema production, assimilation and accommodation, and allowing students to build a better understanding of the focusing function of the slit.

The last component of the demand of the task was understanding the diffractive purpose of the wedge of CD. As noted previously, the first cognitive pathway that was proposed and then drawn on to reduce extraneous load showed no evidence of improving understanding of the functioning of the components of the Mini Spec. Based on the cognitive pathway proposed in Figure 29, the researcher expected that there may be capacity in the working memory for individual sense-making related to germane load in cycle 3 but this did not appear to be the case. Students' responses to the question in the report sheet, ***What is the purpose of the piece of CD in your Mini Spec?*** helped to distinguish between germane load and intrinsic load. Analysis of students' answers after cycle 3 showed that many students attributed a completely incorrect or inappropriate function to the wedge of CD. Therefore, the researcher identified weak or inactivated prior knowledge as the source of the demands of the task which constrained understanding of the function of the wedge of CD in the Mini Spec, see Figure 30.

By the final two cycles, the design-decision was made to alter the question to include more guidance to activate students' prior knowledge. The final version of the question was: ***How is the piece of CD in your mini spec similar to a prism?*** According to the Information Processing Model, the activation of prior knowledge should prime the perception filter to recognize the CD as similar to a prism. Additionally, the stored information of what a prism is could be retrieved from the long-term memory to lower the intrinsic load of the task. The students' working memory processes this information with greater ease, assimilating the function of the wedge of CD with their understanding of a prism. Findings from cycles 4 and 5 showed a large proportion of students achieved a good understanding of the purpose of the wedge of CD. This was a positive finding that supports the researcher's theoretical interpretation of the cognitive pathway proposed and activated in this instance.

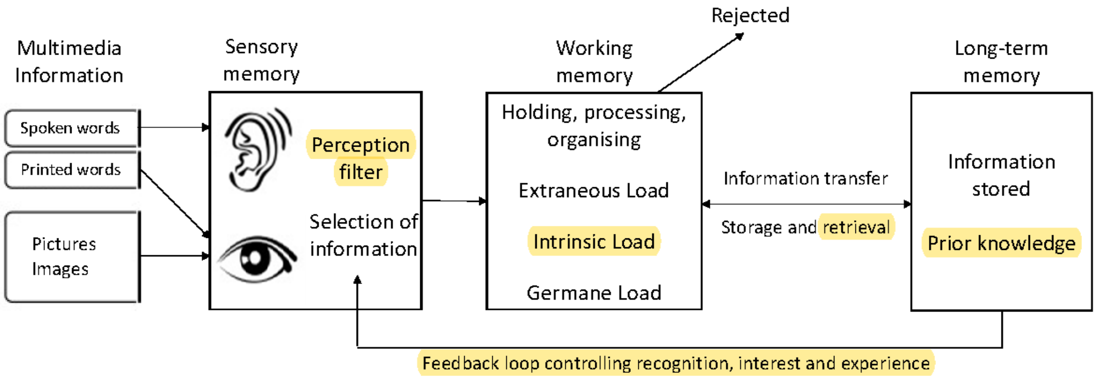


Figure 30. Cognitive pathway targeted to support sense-making of the function of the CD.

The lines between intrinsic load and germane load are very close, and often become blurred. In this instance by *decreasing* intrinsic load we have hypothesized that germane load will in fact be *induced* i.e. students may process and store knowledge of the diffractive purpose of the CD because there is a decreased intrinsic cognitive load.

6.3.2 Addressing conceptual difficulties

The second barrier was that of the inherent difficulty of spectroscopic concepts, i.e. conceptual difficulties. Inherent difficulty immediately suggests a high intrinsic cognitive load associated with these concepts. Here again there is an interplay between high intrinsic load and the available processing capacity required for germane load. In two instances reported in the literature, prior research was conducted to identify difficulties faced by students in introductory spectroscopy followed by the development of teaching initiatives to address these conceptual difficulties: A tutorial "Atomic Spectra" was developed by Ivanjek, Shaffer, McDermott, Planinic and Veza (2015b) to help students relate electron transitions to particular spectral lines and photon energies. Savall-Alemany et al. (2019) developed a teaching-learning sequence in atomic spectra with complimentary teacher and student material, using the format of problem-based learning. There have also been efforts to incorporate online acitivities, simulations or videos to improve students' spectroscopic understanding, but the student profile or topic e.g. UV-VIS was not relevant to this study. This study stands out because the conceptual difficulties faced by students in the laboratory were similar to those cited in literature, however, our means for addressing these difficulties remained grounded in the Mini Spec laboratory exercise, either in the pre-lab activity, construction and use of the Mini Spec, completing the report sheet or through participation in the post-lab collaborative activity.

Several design-decisions were made to support student sense-making, based on potential cognitive pathways. From the onset of the study, a pre-lab activity requiring students to graphically explain the formation of spectral lines was included to support students in sense-making of spectral line formation. This graphical task required the recall of prior knowledge, similar to Figure 30, along with application of the Bohr model of the hydrogen atom to the helium atom. This pre-lab question was purposefully designed to reduce intrinsic load, strengthen pre-existing schema and deepen student understanding and preparing the mind of the student for the processing of new information in the lab.

The introduction of a collaborative post-lab activity to support LO3, spectral line formation, and LO4, classification of spectra, was proposed by the researcher as an additional pathway for individual intrinsic load reduction through the sharing of joint understanding and processing based on the knowledge each student brought with them to the interaction, see enlarged working memory space in Figure 31. The collaborative setting results in a "collective working-memory effect" i.e. an increased capacity compared to the individual's working memory, as the required processing for sense-making was shared among the participants (Kirschner et al., 2011; Kirschner et al., 2018). There were risks or costs involved in introducing a collaborative activity: the structure may apply additional extraneous load in terms of the format of the collaborative activity, group size, group composition, group experience with team work, and individual collaboration skills (Kirschner et al., 2018). These potential forms of load did not appear to create barriers for students' understanding except in infrequent instances when collaboration resulted in the disruption of existing schema that were not robust enough to withstand group interrogation, refer to Section 4.2.3. Overall, the benefits of the collaborative activity outweighed the risks involved, leading to a large number of positive transactions that strengthened the students understanding of spectral line formation and classification, see Section 5.3.

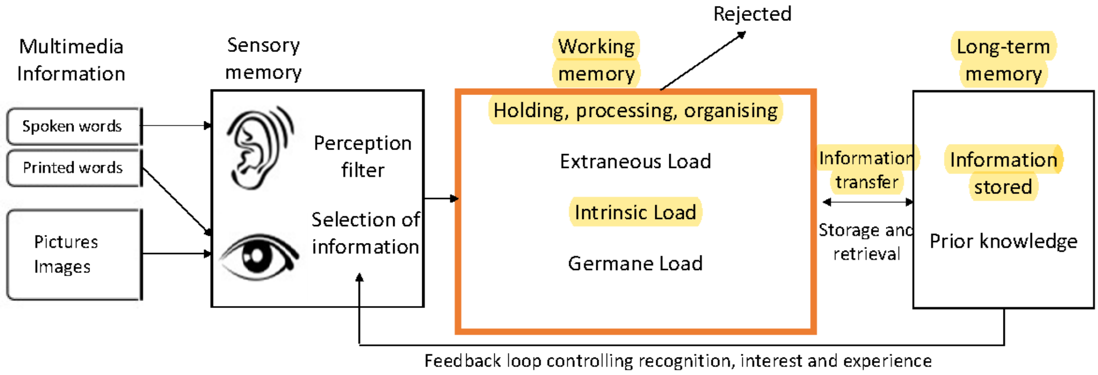


Figure 31. Cognitive pathway supported by a productive collaborative activity

LO4 was addressed in the post-lab activity, but the researcher also sought to address this aspect of the conceptual difficulties faced by students during the laboratory exercise. Findings from the questionnaire data in cycles 1 and 2 revealed student difficulties with classifying spectra as either discrete or continuous based on their observations using the Mini Spec. The researcher identified inducing germane load, see Figure 32, as the mechanism to support students' interpretation of their observations as this load enables schema construction or restructuring of schema for storage in the long-term memory (Sweller, Van Merrienboer, & Paas, 1998). The challenge of this design-decision was to limit extrinsic load and support intrinsic load in implementation, thereby freeing up space in the working memory for induced germane load to be accommodated.

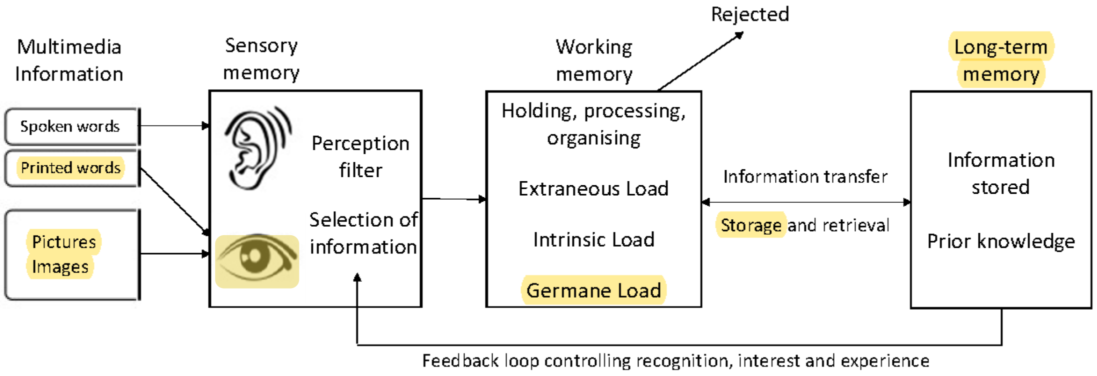
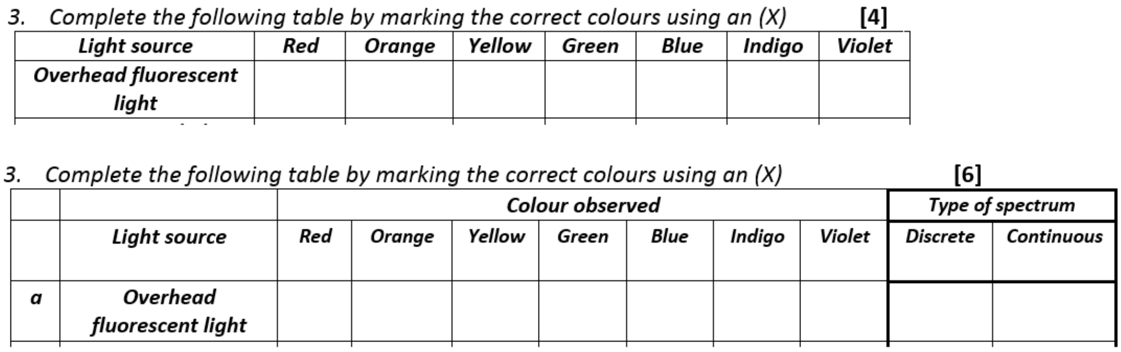


Figure 32. Cognitive pathway targeted to support interpretation of observational data

The researcher's interpretation of the cognitive pathway shows students' spectroscopic observational data as incoming visual information that students gathered. To aid in structuring these observations, a guided table was introduced to the report sheet as another form of visual information, see Figure 33. This table includes the key terms discrete and continuous, printed words to ensure that this information was at the forefront of the students' minds when making their observations. The table was followed by a guided question which aimed to help students interpret their observational results. This question was scaffolded to prompt students to think about the different types of spectra and how they relate to the different light sources. Both of these design-based decisions were made intentionally to increase processing capacity for the germane load by the students.



3. Complete the following table by marking the correct colours using an (X) **[4]**

Light source	***Red***	***Orange***	***Yellow***	***Green***	***Blue***	***Indigo***	***Violet***
Overhead fluorescent light							

3. Complete the following table by marking the correct colours using an (X) **[6]**

		Colour observed							***Type of spectrum***	
	Light source	***Red***	***Orange***	***Yellow***	***Green***	***Blue***	***Indigo***	***Violet***	***Discrete***	***Continuous***
a	***Overhead fluorescent light***									

Figure 33. Section of observation table in report sheets for cycles 1 to 3 (above) and for cycles 4 and 5 (below)

In summary, the success of the design-decisions to achieve LO3 and LO4 through overcoming the barriers of conceptual difficulties varied. The pre-lab activity and post-lab activity were mostly successful in helping students build and solidify the concept of spectral line formation, LO3. The findings from cycles 4 and 5 revealed that the students did interact more actively with the terms discrete and continuous than in previous cycles, however, the understanding that many of the students built around these terms was flawed: 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, LO4.

Understanding the quantum model of the atom, LO5, was the most challenging for the students and had the least direct cognitive support. This final learning outcome was not addressed directly as support was first focused on LO3 and LO4, which encompass threshold concepts for quantization. Language was also a limiting factor on the extent to which conceptual difficulties were addressed. Language as a barrier is discussed in the next section.

6.3.3 Addressing language as a barrier

The third barrier experienced by students was that of language. This barrier was present in itself and was inherent in both the demands of the task and the conceptual difficulties faced by the students. Different facets of this barrier emerged and were addressed within the multiple cycles of design-based research. The complexity of language as a barrier meant that individual cognitive pathways could not be clearly defined. However, language barriers could be interpreted using components of the Information Processing Model and tenets of Cognitive Load Theory.

Even though most students involved in the study were English second language (ESL) speakers, the students themselves were conversant in English. It is the use of English words, be it technical or non-technical, with defined or implied scientific meaning, which created barriers to student learning. These barriers may not be unique to ESL speakers, in fact English speakers also experience scientific language as challenging (Cassels & Johnstone, 1984; Rees, Kind, & Newton, 2019), and foreign or alien (Oyoo, 2007; Oyoo, 2017). In this study, language as a barrier emerged in several different instances:

1. There were high language demands associated with constructing a Mini Spec according to written instructions. These written instructions compromised of non-technical words in a non-technical (a-scientific) context e.g. cut, glue, fold, rectangular, alphabetical, dimensions, iridescent/shiny. Efforts were made by the researcher to use less advanced terminology compared to the original instructions (Schwabacher, 1999), e.g. “cut a hole” was used instead of “incision”, however, complex non-technical terminology could not be avoided in some instances. Therefore, the everyday vocabulary of the students needed to accommodate non-technical words on a spectrum from simple to more advanced. ESL students may not have access to an advanced everyday vocabulary and as such may need to infer meaning from the surrounding text (Rees et al., 2018b; Mayer et al., 2014). Once meaning was created for these words, students were required to hold these words in their working memories, process them accordingly and then carry out the construction instructions. The aforementioned sequence highlights the load on students,

especially the extraneous load of advanced non-technical terminology contributing to the demands of the task.

In referring back to the cognitive pathway given in Figure 29, the researcher provided supplementary, or redundant information to the students in terms of construction templates in various stages of construction. Often redundant information adds to the cognitive load of the students (Chandler & Sweller, 1991), however in the case of novice ESL students the researcher makes a case for the reverse redundancy effect: “The redundancy facilitation hypothesis predicts a reverse redundancy effect in scenarios where redundant material can support basic cognitive processing that is not yet automated in non-native speakers while minimizing extra cognitive load” (Mayer, Lee, & Peebles, 2014, pp. 654). In fact, the researcher proposes that the perception filter was key in prioritising the type of incoming information required by students to complete the task of construction.

2. The terminology relating to the field of optics namely refracts, reflects, diffracts, presented challenges to students in describing the function of the wedge of CD within their Mini Specs. Being a chemistry module, there may have been an incorrect assumption that students have a firm grip on the meaning of these concepts from a physics perspective. However, it seemed that this is not the case as many students were not able to access prior knowledge of these concepts successfully, leading the researcher to propose that these concepts were not embedded in mature schema concerning optics. This lack of readily available prior knowledge resulted in students attempting to formulate their own terminology e.g. “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 & Johnstone, 1984), for example consistent and constituent. Additionally, these technical terms come from the same "word families" i.e. optics and therefore students may conflate their meaning (Rees et al., 2018a), unlike words that merely “sound-alike” and “look-alike” but are unrelated in their meanings. This was further confirmation that the meanings of the words were not well understood; students lacked appropriate prior knowledge to distinguish between or to apply the terms of reflection, 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).

3. Again, language as a barrier, 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 & 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, and provided a source of confusion for ESL students who only see jumping in an upwards direction, i.e. their knowledge construction 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 (replaced with ‘drops’ in cycle 5) between energy levels in an atom and emits a photon***, in favour of a flawed mechanism of spectral line formation, ***Spectral lines are formed when: A photon drops between Energy levels emitting different wavelengths of light.***

4. The confusion regarding classification of spectra may stem from the fact that the terms discrete and continuous are often pitched in contrast to each other in scientific discourse, allowing students to form the misconception that these terms are opposite in terms of meaning, whereas they truly apply to spectra from different light sources (Ivanjek et al., 2020). Another explanation for students’ difficulties with these terms may lie in their dual meanings (Childs et al., 2015). In everyday discourse, the homophone discreet is far more well-known and implies subtlety or tact. Continuous implies something that is un-ending. It is easier to peg scientific meaning to the term continuous as the meaning is similar to everyday use, however, trying to build understanding around the homophone discreet will lead to incorrect schema being formed in the minds of the students as the root meaning of the word discrete is fundamentally different.

   Strictly speaking, the terms discrete and continuous should be classed as everyday terminology according to Oyoo (2007, 2017) as these words are not exclusively used in the sciences. The researcher argues that the term discrete does not actually feature in the everyday modern vocabulary; the word has fallen out of use, however, it is still continued to be used in scientific communities, i.e. 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 or try to construct meaning for this term when discussed in lectures and learning materials like textbooks. This is a barrier 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 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 as described in point 3. Whereas introducing new scientific terminology will come with its own high intrinsic load on the working memory, due to its foreignness (Oyoo, 2007, 2017).

5. The final facet of the language barrier faced by students lay in the term quantization or quantized. These are truly scientific technical terms with no direct links to everyday language. Students avoided using this term in the discussion and when they did try to use it, students struggled with pronunciation. Quantization is an alien term, a term used in the foreign language of chemistry and science, whether students are ESL or not. Students appeared to favour the term discrete over the term quantized, equating the meaning of the two terms, albeit that may students formed flawed concepts of discrete to begin with. The concept of discrete is a precursor to the fuller understanding of the quantized structure of the atom; they are not in fact synonyms as often used by practitioners to lessen the intrinsic cognitive load on students. The novice student requires scaffolding or linking between the terms to be made explicit for mature schema construction to occur, otherwise the word choice and conceptual understanding will remain stunted in the minds of the students.

In this study, both the laboratory exercise and the collaborative activity included questions that required ESL students to strive towards appropriate ways of expressing their developing understanding, which is no small task, especially in a complex topic like spectroscopy. The language difficulties experienced by novice ESL students put additional demands on the processing capacity of the students. Justifiably, developing understanding of the key concepts may be compromised if mindfulness is not practised through awareness of the cognitive load associated with language.

6.4 Reflection on the theory that informed practice

The design-based research approach used in this study ensured that at all times theory and practice were intertwined. From a pragmatic perspective, the chosen theoretical lens and design-based methodology worked well together and were used by the researcher in all the iterative cycles. This interplay has led to new knowledge creation in the context of this study: ***conceptual difficulties*** was not the only barrier that novice students faced in spectroscopy, but the demands of ***language*** and the ***demands of the task*** presented two additional primary barriers.

Cognitive Load Theory and the inter-linked memory components of Information Processing Model were used by the researcher to identify and address barriers to novice students' understanding of emission spectroscopy. A major criticism of Cognitive Load Theory is that it is not falsifiable (Gerjets et al., 2009). It is true that the cognitive pathways hypothesised by the researcher were not directly measurable and the memory components thereof are merely constructs that suggest how learning takes place in the minds of the students. In this study, the design decisions to manage cognitive load where done in particular cycles, the assumption is that the interpreted cognitive pathways allow for benefits to remain for later cycles. Likewise another assumption is that the cognitive pathways interpreted are the same for all students and will have similar effects on students' experiences in the laboratory. However, these assumptions did not undermine the usefulness of interpreting cognitive pathways to inform practice, as is evidenced by the general improvement in students' understanding over several cycles of design-based research.

Further known limitations of Cognitive Load Theory lie in the fact that entanglement often occurs between the three types of load (De Jong, 2010) and that germane load, in particular, is difficult to isolate and to measure making it redundant in the eyes of some scholars (Kalyuga, 2011). When mapping the cognitive pathways underpinning the conceptual difficulties and language barriers in this study, the distinction between germane load and intrinsic load was not always clear. Added to this is what is known as the transfer paradox (Van Merriënboer et al., 2006), abundant use of instructional methods that increase germane load in complex learning tasks e.g. feedback and worked solutions often do not result in long-term learning, learning transfer or problem solving ability. That is, genuine learning, which defines germane load, may not occur if the germane load applied is too high! These difficulties in the theory are troubling but may be solved if the intention of the instructor or expert is reflected upon. Are we deliberately imparting schema for students to become more expert? Or do we want to allow students the processing capacity to arrive at their own knowledge? In other words, understanding, defining and manipulating germane load may lie in whether we ***apply*** or ***induce*** germane load, respectively. A cognitive pathway which ***applies*** germane load will be one in which the expert intentionally scaffolds the task, see Figure 32, whereas ***inducing*** germane load will be the result of intentionally lowering the intrinsic load and therefore allowing students the opportunity for individual or joint sense-making, see Figure 30 and 31, respectively. The choice of whether to ***apply*** or ***induce*** germane load will vary on a task by task basis, taking into account the delicate balance of student expertise and the complexity of the learning task at hand.

Cognitive Load Theory has developed in recent years in its capacity to incorporate additional theories or constructs (Sweller & Paas, 2017). The non-rigid constructs of Cognitive Load Theory allowed language barriers to be identified and supported by viewing language as integral to the different types of load: intrinsic, extraneous and germane. Much attention has been paid to the relationship between individual cognitive load and language (Cassels & Johnstone, 1984; Johnstone & Selepeng, 2001; Mayer, Lee, & Peebles, 2014). Kirschner et al. (2018) detail the high intrinsic load and element interactivity of translation for an individual. However, language does not feature as one of the Collaborative Cognitive Load Principles, it is merely implicit in many of thereof e.g. the format of the collaborative activity in terms of guidance and support, team size, team composition team domain expertise and team collaboration skills (Kirschner et al., 2018). As language is such a large contributor to so many facets of collaboration it is arguable that language should be recognised as a primary principle for guiding instructional design albeit for individual or collaborative settings.

In general, Cognitive Load Theory was appropriate given the novice nature of the students and the level of understanding required. The researcher, as more expert in the field of spectroscopy, could propose cognitive pathways to improve the understanding of novices, as she herself had advanced along the same continuum from novice towards expert that was expected of the students. That is, the researcher had to progress from similar lower level schemas towards higher level schemas in emission spectroscopy, giving the researcher greater insight into the difficulties that novice students were facing.

The combination of chosen theoretical lens and design-based research cycles was valuable as it allowed for interpretations and inferences by the researcher which resulted in improved practices in the spectroscopic laboratory context. However, this was only achieved to varying extents over multiple cycles; time and resources are some of the costs of such a research design (Anderson & Shattuck, 2012). Added to this was the number of data collection tools, questionnaires, report sheets, recordings, used in an integrative fashion to gather findings that could be interpreted using the theoretical lens of the study. The flexibility of design-based research coupled with Cognitive Load Theory may be advantageous for both researchers and practitioners seeking a means to interpret and address layers of difficulties faced by novice students in a complex environment, like the emission spectroscopy laboratory.

6.5 Summary

Three primary barriers to students' understanding of spectroscopy were identified as the demands of the task, conceptual difficulties, and language. The primary barriers appeared to different extents in the different cycles of design-based research and therefore may not be exhaustive of difficulties that novice students may face in this topic. Each of these barriers represents a grouping of instances where the development of students' sense-making or understanding was hindered. Hypothesized cognitive pathways were used by the researcher to interpret and address the barriers faced by the students.

Cognitive Load Theory informed practice for all the cycles of design-based research. All design-decisions were grounded in the theory, that is, use of the theory remained high across all five cycles. However, the researcher contests that the distinction between applied and induced germane load will make the theory easier to use. Cognitive Load theory gave substantial backbone for answering the second research question, ***How were the barriers to student understanding of emission spectroscopy addressed?*** and as such informed decisions that addressed the three primary barriers experienced by novice students in spectroscopy to varying extents.

Language as a barrier was multi-faceted as was the case for the other two primary barriers, however, it was more complex to interpret. The findings suggest that over-simplifying concepts e.g. equating discrete spectra and quantization, or, using non-technical terms e.g. jumps, whose meaning differs in the minds of ESL students, may ***create*** barriers for students instead of lowering intrinsic cognitive load. Additionally, the use of outdated everyday words in the scientific communities e.g. discrete may create further barriers as these unfamiliar everyday words are not correctly linked in students' mental schema, nor are they able to appropriately construct meaning for these terms if a false impression of a dichotomy is created between terms e.g. discrete vs. continuous. This study shows that a balance must be struck between simplifying language for ESL students and the load the simplified language places on ESL students. Inadvertently, practitioners who ground themselves in Cognitive Load Theory may be increasing the load on students! A suggestion is to place more emphasis on imparting our own expert schema into scaffolded linkages between concepts for the students in complex topics.

CHAPTER 7: Conclusion

7.1 Introduction

This is the final chapter of the thesis and includes a general overview of the design of the study as well as a summary of the findings and their significance. The limitations of the study along with future avenues for development are also included to give a perspective of the shortcomings of the study balanced by its future research possibilities. A large section of this concluding chapter offers pertinent implications for practice that may be of interest to fellow practitioners.

7.2 Overview of the study

The overarching aim of this study was to identify and address barriers to understanding emission spectroscopy for novice university students in a chemistry laboratory. Five key learning outcomes outlined the intended mastery of students' understanding of spectroscopy at first-year level. These learning outcomes included understanding the basic functioning of the components of a spectroscope and understanding spectral line formation, spectroscopic classification and line intensity. Students' level of mastery of the five learning outcomes during a laboratory exercise flagged barriers to students' understanding. The laboratory exercise required students to construct and use a Mini Spec to observe spectra from everyday light sources, and to complete a guided report sheet. The study was conducted over several years and included five cycles of design-based research. In the first two cycles, quantitative data collection tools were used primarily with large student samples. These findings gave indications of areas of focus for the remainder of the study. In the latter three cycles, sample sizes were substantially smaller allowing for in-depth analysis of student sense-making. Cognitive Load Theory and the Information Processing Model informed decisions made in each cycle of the study, which led to progress in addressing the barriers faced by first-year students.

7.3 Summary of the findings

Each new cycle of the study generated new insights and a deeper understanding of the barriers to understanding, whether it was associated with the tasks that the students had to carry out or conceptual challenges associated with the topic itself. In general, the quality of students' understanding of the five learning outcomes improved with each cycle. The five learning outcomes included the slit as the focusing component (LO1), the CD as the diffraction grating (LO2), the formation of emission lines (LO3), the classification of spectra (LO4) and the interpretation of emission spectra as evidence of quantization (LO5). The last two learning outcomes remained relatively more difficult for students than the understanding the components of the Mini Spec or understanding spectral line formation. Additionally, mastery of one learning outcome did not necessarily translate into mastery of other learning outcomes. All students benefitted from the laboratory exercise, irrespective of their overall performance in chemistry.

In summary, the study generated the following answers to the two research questions:

1. What were the barriers to understanding emission spectroscopy and how were they identified?

The difficulties that students faced in understanding spectroscopy were grouped according to three main barriers: the demands of the task, conceptual difficulties related to the topic and language.

The construction time it took for students to build the Mini Spec and their limited understanding of the functions of the Mini Spec components (LO1 and LO2) were grouped under the banner of the ***demands of the laboratory task***. In cycle 1 it was evident that poor student performance in the lab report sheet could be linked to cognitive overload arising from the demands of interpreting the written construction instructions (see Appendix A). The demands of the task also included understanding the function of the Mini Spec components i.e. the slit for focusing incoming light and the wedge of CD as a diffraction grating; understanding these standard components is considered a prerequisite for understanding the basic functioning of spectroscopic instruments in general.

Even though most students were able to demonstrate an understanding of how spectral lines are formed very few students were able to interpret the meaning of the term discrete or arrive at a model of spectral line intensity and quantization that is acceptable for their level of academic development. ***Conceptual difficulties*** manifested in the students' report sheets and in their attempts at joint sense-making in the collaborative activity.

Language was classified as the final barrier that represents a grouping of several types of language difficulties experienced by the students. Language difficulties underpinned large portions of the two barriers mentioned above but also created difficulties in understanding of spectroscopy in and of itself. Language difficulties were tracked throughout the study, from interpretation of written instructions, to the nuances of non-technical terminology used to describe electron transitions, and the technical terminology used in the field of optics and quantum theory.

2. How were the barriers to student understanding of emission spectroscopy addressed?

The researcher used cognitive pathways to identify possible origins of learning breakdown; these pathways informed the refinement decisions made in subsequent cycles. Cognitive pathways were representations of the Information Processing Model in which memory components and types of cognitive load form a pathway for the processing of information and experiences. These cognitive pathways were used to create hypotheses to identify barriers and to inform refinements that may reduce these barriers.

The demands of the task were addressed firstly by providing students with templates in various stages of construction; the extraneous load required to decipher written instructions may have been reduced as the perception filter was able select lower-demand visual images to hold in the sensory and working memories. Sense-making of the focusing and diffracting components of the Mini spec was supported with guided questions. The first cognitive pathway informed extraneous load reduction and the second cognitive pathway suggested that activating prior knowledge would help alleviate intrinsic load to strengthen schema formation, see Figures 29 and 30.

The hypothesized cognitive pathways which supported conceptual difficulties identified high intrinsic load and a low capacity for germane load as key facets that may have been limiting students' understanding. The pre-lab activity was designed to activate students' prior knowledge on emission line formation and thus decrease intrinsic load on students when it came to communicating the mechanism of spectral line formation and the variation in the intensity of emission lines. The design of students' report sheets was refined to include the terms continuous and discrete in their observational data tables followed by a guided question. According to the interpreted cognitive pathways this should have provided more structure to students' observations using the Mini Spec, stimulated their engagement with these complex terms and allowed cognitive capacity for processing and understanding these terms in a real-life context, see Figure 32.

The hypothesized cognitive pathways assisted in addressing the two primary barriers to varying extents. The demands of the task were reduced significantly whilst there still remains room for improvement in addressing the conceptual barriers. Elements of the cognitive pathways and principles relating to Cognitive Load Theory were used to interpret the diverse language difficulties faced by students in this study. Some of the difficulties could be easily addressed e.g. choosing non-technical terminology with more uniform meaning i.e. "drops" instead of "jumps", or, providing construction templates to reduce language demands. The difficulty associated with the phonetic closeness of optics terms and the conflation of their meaning remained unresolved, i.e. reflect, refract, "defract" and diffract; plans for strengthening prior knowledge and exposure to these terms were suggested for future cycles of design-based research. Similarly, students' difficulty with the term quantized or quantization may be supported by continued use by the practitioner or a scaffolded activity as suggested at the end of Chapter 4. The understanding of the outdated everyday term, discrete, may also be addressed to some extent through either replacing the term with a more common everyday word, developing a new scientific term or further efforts to help students construct meaning for discrete.

7.4 Reflection on Research Design

In this study, cognitive learning theories, namely Cognitive Load Theory and the Information Processing model, were used to inform the cycles of design-based research. Cognitive Load Theory is not without its limitations and is often criticized for its unfalsifiable nature; however, the resurgence of Cognitive Load Theory in education literature positions the design of this study among current research trends. Design-based research was the chosen methodology for this study. This is a fairly new approach which has come to the fore in recent years, over-taking Action Research due to the significance afforded to the role of theory in design-based research.

Over-and-above the current nature of both the theory and the methodology, the combination of Cognitive Load Theory and the Information Processing Model with design-based research proved advantageous in identifying and addressing the barriers faced by the students. The research design purposefully managed the relationship between the educational context, desired learning outcomes, and the cognitive demands placed on the student in this study. This combination also allowed for the interpretation of language barriers, and, for the researcher to give recommendations for the expansion of Cognitive Load Theory, especially in collaborative settings, to include language demands as a key construct.

7.5 Significance of the study

The design of this study allowed the researcher to make a practical contribution to emission spectroscopy education by identifying and addressing barriers faced by novice chemistry students in first-year chemistry. The first contribution was that the merger of Cognitive Load Theory and design-based research has high value in the complex laboratory context and could also be coupled with the inherently challenging and abstract topic of spectroscopy.

The second practical contribution was the finding that conceptual difficulties were not the only barriers experienced by novice students in spectroscopy: the demands of the task and language barriers were also very significant in students' developing understanding. In this study, the three primary barriers were found to include multiple contributing difficulties that only emerged over several cycles of interventions.

This study sought to make a theoretical contribution by unpacking various language difficulties faced by novice ESL students in spectroscopy and supporting them through Cognitive Load Theory, over several design-based research cycles. In literature there is a focus on the difficulties associated with using everyday terminology in the scientific context (Oyoo, 2017; Rees et al., 2018a). There is also a general concern about the demands that students face with the language of chemistry and communicating concepts across the macro, sub-micro and symbolic levels (Kelly, 2010; Taber, 2009; Talanquer, 2011). However, there are no studies examining language difficulties in the teaching of spectroscopy, with all spectroscopy education studies focusing on the inherent conceptual difficulties instead (Ivanjek et al., 2015a, 2020; Körhasan & Wang, 2016). The findings of this studied showed clear evidence of difficulties associated with using non-technical words to describe concepts in spectroscopy and went a step further in isolating outdated terminology and conflicting ESL understandings of animisms as further sources of difficulties. The cognitive theoretical lens of this study informed the identification of these barriers and should give support to practitioners leading discussions in complex topics like spectroscopy and designing learning materials.

Most of this thesis dealt with analysis of students' developing understanding and the barriers that stood in the way of sense-making and understanding in emission spectroscopy. The accompanying publication to this thesis highlights the advancements made in making emission spectroscopy accessible to both novice students and their communities through limiting the extraneous load on students in the laboratory and providing them with structured laboratory exercise. In this publication the refinements of the Mini Spec, the construction methods and report sheet are discussed. After the laboratory exercise, the Mini Spec was found to travel great distances with students across the country. The Mini Spec was discussed in multiple languages by students sparking enjoyment, learning and motivation to learn science in the students' homes and communities. In tying the thesis and the article together, we can boldly state that this work represents a significant contribution to novice emission spectroscopy education: we have designed and refined a laboratory experiment that gives students the thrill of seeing real-life spectra and the satisfaction of sharing it with their home and communities, along with the design of a reliable evaluative rubric for educators to use in assessing this laboratory experiment and a developing understanding of the barriers faced by novice students in spectroscopy.

7.6 Limitations of the study

There are several limitations of this study, firstly the multiple-choice nature of the majority of the pre- and post-lab items used in throughout the study. There is often an element of guessing when students are provided with multiple choice options. In terms of the analysis of the students' report sheet, the researcher used member checking and a Spearman's *rho* coefficient to ensure the formation of high quality codes which were utilised as consistently as possible. Unfortunately, there will always be human error attached to data collection methods and bias in interpretations made by the researcher, although this bias is sometimes argued as a strength for the research in terms of deep insight and understanding of context (Anderson & Shattuck, 2012).

The findings of this research were generated using mixed methods with a heavier focus on quantitative methods in the first two cycles. Findings for cycles 3 to 5 were richer, qualitative interpretations of students' understanding. Qualitative findings are limited by their generalizability and quantitative results by their specificity. The trustworthiness of the findings of this study is strengthened by the fact that they build on each other. The concern that the findings of this study may only be reproducible or only applicable in similar contexts is addressed by the fact that the barriers that were uncovered are based on a strong research design which may make them more generalizable than findings from either a pure qualitative or quantitative research design.

Design-based research studies are "inevitably unfinished" (Stewart and Williams, 2005). In this study, although the researcher was able to identify three primary barriers, the extent to which these barriers were addressed varied greatly. In addition, the theoretical lens and research design have known disadvantages in literature, see Chapters 2 and 3, respectively. These factors are acknowledged as a possible limiting influence on the strength of the study.

7.7 Implications for practice

Fully understanding chemistry knowledge requires students to move between the macro, submicro, and the symbolic levels of representation or a version thereof (Johnstone, 1991; Taber, 2013; Talanquer, 2011). Without an opportunity to interact with spectroscopy on a macroscopic level, spectroscopy will remain abstract and difficult to master. The hands-on laboratory exercise used in this study exposed novice students to the macroscopic level of spectroscopy and emission lines. The Mini Spec laboratory exercise is a low cost and low stakes way in which practitioners can easily expose learners and students to introductory spectroscopy. The hands-on exercise including the construction, observations and guided report sheets made spectroscopy tangible for extended programme students, enabling a growth of confidence and motivation which reached beyond the classroom. It is reasonable to expect similar successes in similar contexts.

The practitioner should, however, not lose sight of the fact that spectroscopy is a complex topic and the lab environment is also complex in and of itself. The use of the Mini Spec on its own is not enough to mitigate the cognitive load experienced by students and should be supported with well-designed learning materials, such as the report sheet used in this study. The targeted reduction in cognitive load, guided interpretations of observations and deliberate activation of prior knowledge should allow for more meaningful learning in either the laboratory or classroom environments.

In addition, the use of pre- and post-lab activities have been recommended in literature to stimulate meaningful learning in complex laboratory settings (Reid & Shah, 2007). The spectroscopic laboratory exercise refined in this study was 'sandwiched' between a pre-lab and a post-lab activity and, as an obvious consequence, there was greater scope for sense-making in spectroscopy. Moreover, the use of two very different techniques, the pre-lab activity which was individual and visual in nature whereas the post-lab activity was verbal and relied on social transactions, stimulated very different cognitive pathways by activating and optimising different cognitive components. Due to time constraints, practitioners often only use one side of the cognitive sandwich, however, findings from this study recommend diverse pre- and post-lab activities to support student processing in complex learning environments.

The format of the post-lab activity used in this study had benefits and disadvantages. The practitioner must always be aware that the design of the post-lab activity must speak to the goals of the post-lab activity and consider whether it is simply a consolidation exercise or should it be part of the students' sense-making journey. The choice of collaborative tasks such as a post-lab activity allowed for both sense-making and sense-breaking beyond the confines of the laboratory exercise. During the laboratory exercise, students had built concepts that were both complex and freshly formed. Challenges to these concepts or strong arguments in favour of alternate concepts in the collaborative setting sometimes led to weakening of understanding in emission spectroscopy. Although this was infrequent compared to the positive transactions that enriched students' understanding, it serves as a necessary cautionary note to the practitioner.

Balance is required in a post-lab activity: if students were merely provided with the correct answers and asked to motivate or explain their observations, the richness of thought in the discussion may be diluted. Guidance during the post-lab activity is as important (if not more so) than during the laboratory exercise itself where concepts are being formed, as unfavourable changes to understanding in this final activity will only be challenged when the students revisit spectroscopy for assessment purposes or later in their academic careers. It may be prudent to embed a feedback mechanism in the post-lab activity, for example, a demonstrator may quickly look at the group answer after the activity, point out any mistakes (without giving away the correct answer) and allow students the opportunity to revise their answers and hence revise alternate concepts that may have been formed or persist from the laboratory exercise.

Language has a resounding implication on practice in spectroscopy. It is clear that students face more than just the known conceptual difficulties, there is load on the students in terms of language and terminology. Some words look or sound *intimidating* e.g. quantized, or too *similar* e.g. reflection, refraction and diffraction, however, creating well-formed schema around these terms requires constant engagement with them by the educator and the students. Practitioners may find themselves oversimplifying language during discussions of complex topics such as spectroscopy to minimise the load on the students, however, we may not be doing the students any favours. By using everyday words to describe scientific phenomena, like electron transitions, creates unnecessary barriers as everyday meaning varies with the individual whereas scientific terminology has a fixed meaning. It is also important not to conflate words such as discrete and quantized in our teaching, the former is a conceptual stepping stone to the latter and by conflating the two students may miss the vital step needed to understand the structure of the atom.

7.8 Recommendations for future research

Design-based research is cyclic in nature, and because of this, large amounts of time and resources are needed to sustain a study to its ultimate conclusion, if it is ever reached (Anderson & Shattuck, 2012). Much work still needs to be done to support students understanding of the term discrete along with facilitating an appropriate mental model of the quantization of the atom. Cognitive Load Theory and the Information Processing Model could be used to inform future cycles of design-based research; however, other theoretical lenses may have greater utility in unpacking these complex topics in practice. The theoretical lens would be for the researcher to evaluate, along with the choice of whether to persist with cycles of design-based research. Likewise, the coding of positive and negative social transactions in the collaborative transcriptions could be enriched with other procedures such as discourse analysis. Even the use of the pre-defined learning outcomes as an evaluative framework could be further refined, expanded to include LO3, or replaced.

The emergence of two additional barriers, the demands of the task and language, along with known associated conceptual difficulties may be transferrable to other complex laboratory environments. Analytical instrumentation often remains a “black-box” for students in the laboratory, with its complex functioning and challenging data for interpretation. This may be an ideal area for further research into the applicability of the barriers discovered in this study and the cognitive pathways used to address them. However, further research may encompass *any* laboratory environment, which is truly a complex environment, where students need all the support possible, especially as the recent COVID-19 pandemic may have left students with limited laboratory exposure as a foundation for their future studies.

Language in teaching and learning chemistry will continue to be a challenge, it is a field so vast and deep that it was impossible to fully explore within the scope of this study. Facets of language difficulties may be worth pursuing in future research, especially ESL students' propensity to ignore complex sounding words. The deliberate omission of terminology with scientific meaning limits the depth of concept development in the minds of the students. Research that seeks to actively engage students in complex terminology may help build student confidence, scientific identity, as well as facilitate novice schema production.

7.9 Personal reflections of the researcher

The beautiful thing about learning is that it is an on-going process throughout our lives. Having the privilege to peek into the learning process of students over the many cycles in this study has allowed me to contribute to their learning in spectroscopy as well as enrich my own. In learning we are traversing the continuum from novice to expert, whether anyone can ever be fully expert is a point for debate, but as human beings we can assist one another in the learning process by passing on expert schema or at least allowing novices the opportunity to develop their own.

I have realised that sometimes the decisions you make in a study are not as effective as you hoped they would be; reducing the demands of the task on the students did not simply make all other barriers disappear. Despite grounding all the design decisions in theory before implementation, sometimes there were unexpected consequences that arose that needed to be interpreted and managed. I feel that this was due to the complex nature of the topic I was dealing with in this study and the intricate nature of learning and information processing, but it is also a facet of reality that we all deal with. The contextual nature of design-based research helped me deal with reality as it unfolded.

This study put me on a long journey to unearth difficulties and support students' understanding in spectroscopy. The phrase, "Rome wasn't built in a day", is apt when I reflect on this journey. It is also a journey that my students and I were not taking alone: my supervisors have walked this road with me; helping me build the discipline and grit necessary to complete this study and continue as an early career researcher.

7.10 Concluding remarks

Introductory spectroscopy serves novice chemistry students in understanding the evolution of the model of the atom. The atom and its subatomic components, as well as their arrangements and interactions, form the basic building blocks of chemistry theories of bonding and reactivity. The introduction of a laboratory exercise on spectroscopy was necessary as it allowed novice students to interact with an abstract and complex topic whilst learning about the fundamentals of a basic spectroscopic tool.

Over the many cycles of this study, findings in five key learning outcomes indicated that novice students experience more than the known conceptual difficulties in spectroscopy: there are task demands as well as language barriers. Language barriers were seen in the cognitive load associated with written instructions and specific terminology. Cognitive Load Theory was used to interpret and inform design-based decisions that refined the laboratory exercise; however, future cycles will still be needed to fully address all facets of the barriers faced by novice students.

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APPENDICIES

A: Journal of Chemical Education, Mundy and Potgieter (2020)

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

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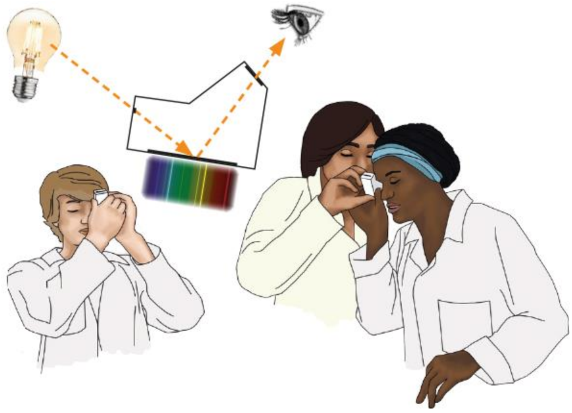
Abstract

This article reports on the introduction of a simple, portable, low-cost and hands-on spectroscopic 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 spectroscopic 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 spectroscopic 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 spectroscopic 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 spectroscopic 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 spectroscopic tool for the laboratory session on this course, based on the following considerations:

- Cost, as funding was limited
- Portability of the spectroscopic 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.

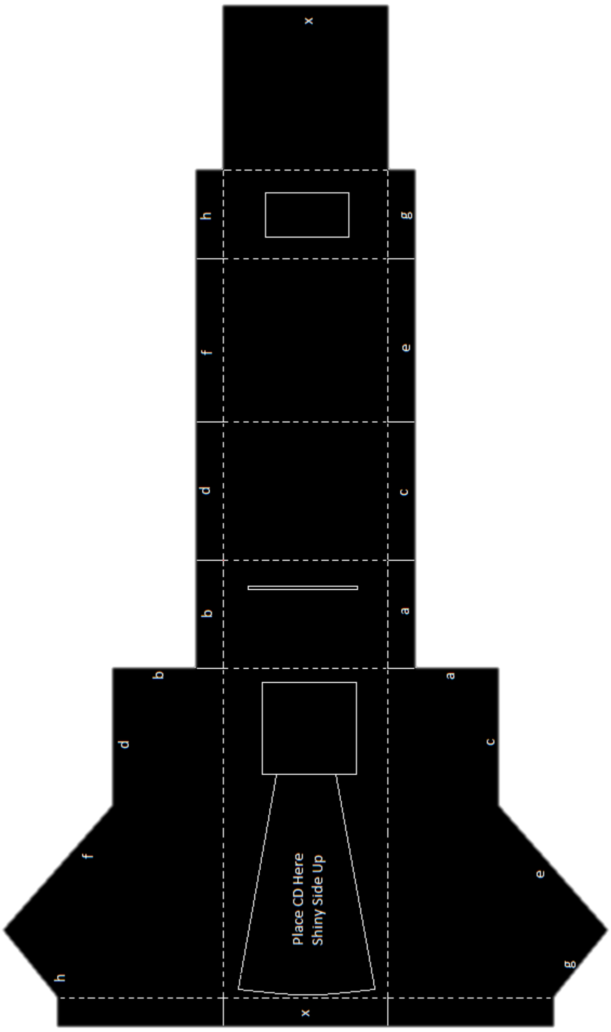


Figure 1. Refined Mini Spec template.

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.

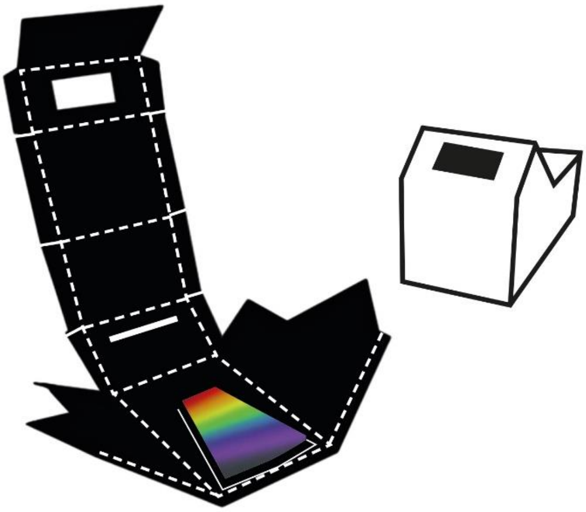


Figure 2. Diagram of the construction references provided in level 2 of refinement.

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.

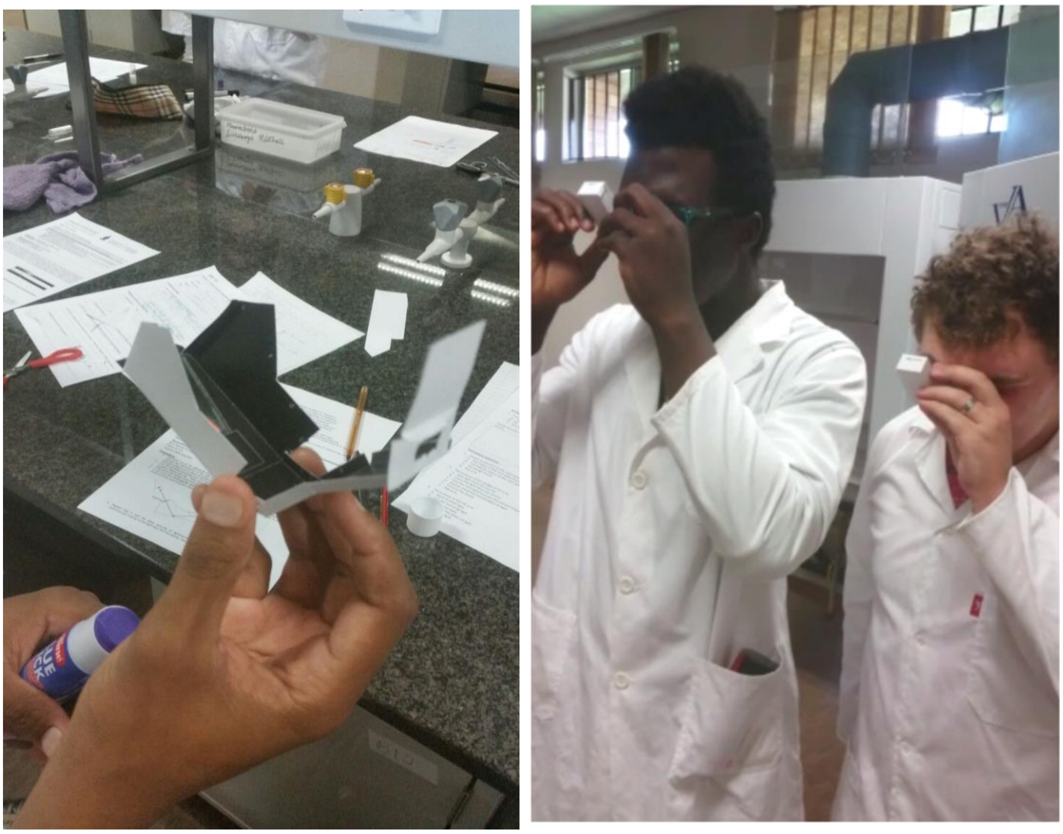


Figure 3. Student constructing a Mini Spec (left). Students using their Mini Specs to observe overhead fluorescent light (right).

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 spectroscopic 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.

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.

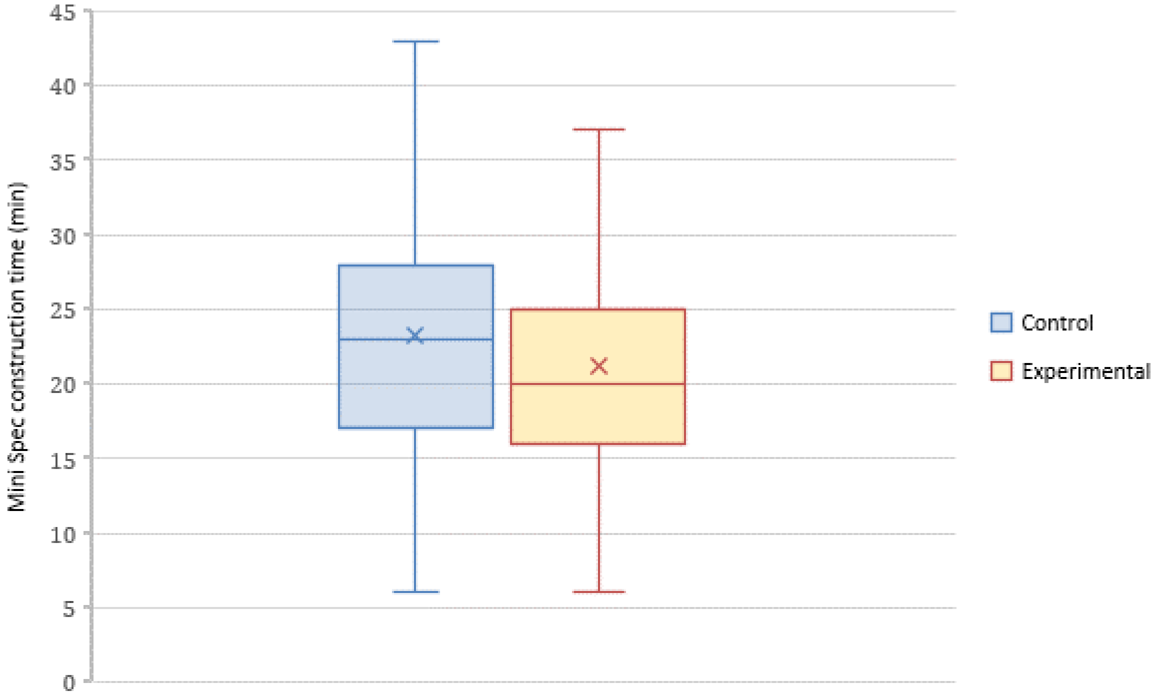


Figure 4. Box and whisker plot of construction time per group

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.

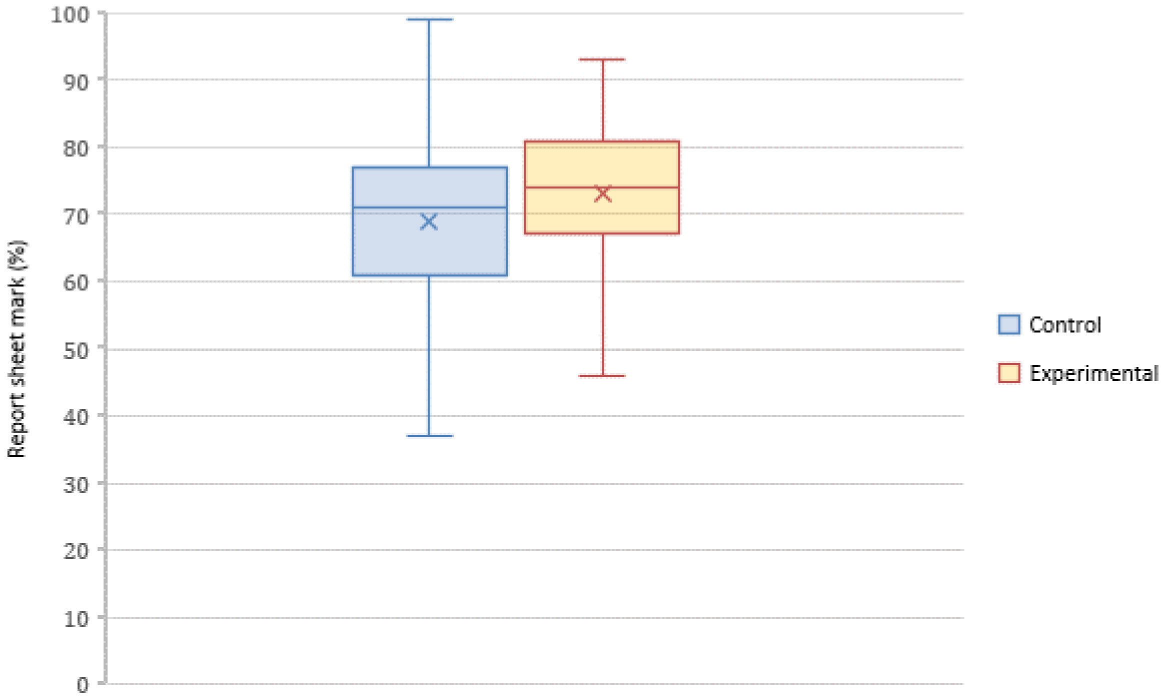


Figure 5. Box and whisker plot of student performance in the report sheet per group

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).

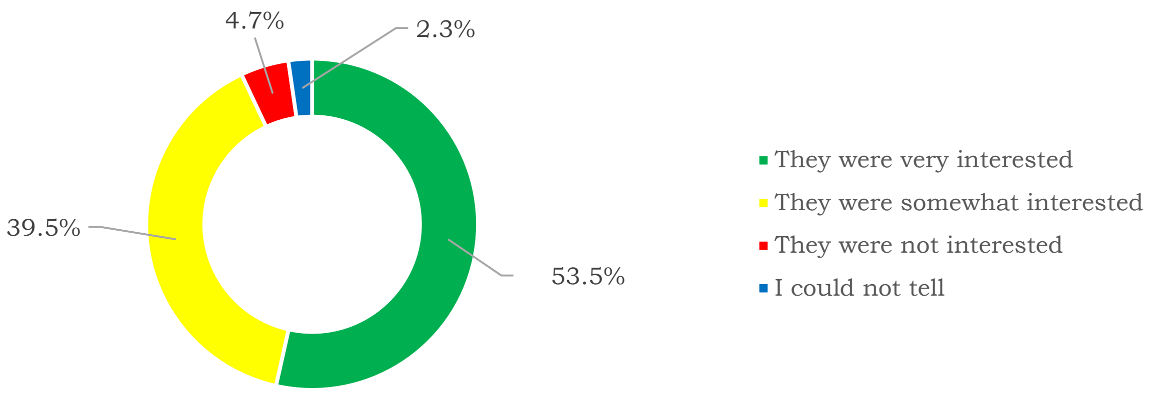


Figure 7. Response data from item Q5 of Qualtrics survey (What was their reaction to the Mini-Spec?)

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 spectroscopic 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 were 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.

Associated content

Supporting Information

Mini Spec Template (DOCX)

Experimental manual (DOCX)

Report Sheet (DOCX)

Tips for Instructors (DOCX)

Voluntary online Qualtrics survey for students (DOCX)

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Acknowledgments

We thank the academic staff and demonstrators for their assistance and observations. We also wish to thank the students who responded to the survey and shared their Mini Specs with the people around them. The research was supported by the National Research Foundation of South Africa (Grant Number 111816). Finally, we thank Glenda Brits for Fig. 2, Fig. 6 and the graphical abstract.

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B: Meta-analysis Methodology

Google Scholar was chosen as the search engine for the study as it is a free, open-access platform compared to other commercial and scholarly platforms. Limitations in the shallow depth of Google Scholar are acknowledged, for example only a citation may be available and not the full text. Such a shortcoming is compensated for by the vast breadth of scope provided by Google Scholar: in this meta-analysis, the frequency of hits is of importance, not whether the full text is accessible via Google Scholar.

The number of hits per year were recorded from 1900 to 2020 using the following search terminology: **“cognitive load” AND education* OR instruction* OR learn***. The requirement was that the words “cognitive load” must be side by side in the digital source, that is, the search did not include results where “cognitive” and “load” were used in separate instances in the sources. In order to make the search relevant to education, the term “cognitive load” was paired in the search with at least one of the three educational synonyms (education, instruction or learn).

An identical search was conducted from 1900 to 2020 using the following search terminology: **constructivism* AND constructivist* AND education* OR instruction* OR learn*.** The three educational synonyms used were identical, eliminating any bias or potential weakness in the selection of terminology. The learning theory could not be simply stated as construct* as preliminary searches yielded findings of no concern.

The second leg of the investigation was based on a qualitative analysis of abstracts. The abstracts were collected from the first 6 months of 2018 using the same search term (**“cognitive load” AND education* OR instruction* OR learn*)** as used to generate a pool of publications. Of the first 100 most relevant hits discerned by the Google Scholar algorithm, 42 included the term cognitive in the title. Furthermore, the abstracts were manually verified to ensure that the term "cognitive" was indeed being used in terms of Cognitive Load Theory.

The 42 abstracts were analysed in three separate rounds to discern the level of instruction, educational discipline and current directions in Cognitive Load Theory research. Analysis was done using Atlas.ti v8.

Pre-lab ex.	**/8**	
Report	**/16**	
Bonus participation	**/2**	
Total	**/26**	**%**

C: Report sheet: Cycle 3

Experiment 3: Emission Spectra & Spectroscopy

Surname		**Initials**	
Student number		**Group**	
Signature			
Date			

Pre-laboratory exercise:

1. *Make a labelled drawing of the complete electromagnetic spectrum.* **[4]**

2. *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]**

Experiment*: The Mini spec (Schwabacher , 1999)*

Show your tutor your completed mini spec

Construction mark: __ /2
Tutor signature: ____________________

1. *What is the purpose of the piece of CD in your Mini Spec?* **[2]**

2. *What is the purpose of the slit in your Mini Spec?* What would happen if the slit was too large? Or too small? **[4]**

3. *Complete the following table by marking the correct colours using an (X)* **[4]**

Light source	***Red***	***Orange***	***Yellow***	***Green***	***Blue***	***Indigo***	***Violet***	***Other***
Overhead fluorescent light								
Energy saver light								
Incandescent light								
Natural sunlight								

4. *When viewing artificial light sources you see emission lines with your Mini Spec. What is the significance of this finding?* **[2]**

5. *Some of the emission lines appear brighter than others. What is the significance of this finding?* **[2]**

Pre-lab ex.	**/8**	
Report	**/18**	
Total	**/26**	**%**

D: Report sheet: Cycle 4 and 5

Experiment 3: Emission Spectra & Spectroscopy

Surname		**Initials**	
Student number		**Group**	
Signature			
Date			

Pre-laboratory exercise:

1. *Make a labelled drawing of the complete electromagnetic spectrum.* **[4]**

2. *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]**

***Experiment**: The Mini spec (Schwabacher , 1999)*

Show your tutor your completed mini spec

Construction mark: __ /2

Tutor signature: ____________________

1. *How is the piece of CD in your Mini Spec similar to a prism?* **[2]**

2. *What is the purpose of the slit in your Mini Spec?* What would happen if the slit was too large? Or too small? **[4]**

3. *Complete the following table by marking the correct colours using an (X)* **[6]**

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

4. *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.* **[2]**

5. *For a particular light source, some of the emission lines appear brighter (or more intense) than others. What is the significance of this finding?* **[2]**

E: Pre-lab Questionnaire: Cycle 1 and 2

This questionnaire is part of a study to explore the benefits of using the Mini spec (Schwabacher, 1999). Participation in the study is voluntary. No marks are allocated for your responses, don't stress.

Instructions

USE SIDE 2

- You will need to complete a pre-prac and a post-prac questionnaire
- **<u>Do not</u>** fill in any of your details (name, surname, student number etc.). Your responses are anonymous.

<u>Background information</u>

1. Select the statement which **best** described your practical experience with light at high school
   A. We did not do any experiments
   B. Our teacher showed us demonstrations or simulations of light and diffraction
   C. As a learner we got to use prisms and/or slits to look at light by ourselves or in small groups
   D. We were exposed to a real spectroscope in class
   E. Both Option C and D
   F. I can't remember

<u>Conceptual questions</u>

2. Which component of the mini spectroscope acts as a prism?
   A. I am not sure
   B. The shape of the mini spec
   C. The interior colour of the mini spec
   D. The wedge of CD

3. The purpose of the wedge of CD is to:
   A. I am not sure
   B. Split light from the source
   C. Focus the light from the source
   D. Give the mini spec the correct shape
   E. Absorb unwanted wavelengths of light
   F. None of the above

4. The purpose of the slit is to:
   A. I am not sure
   B. Block emitted light
   C. Dim the incoming light
   D. Protect your eyes
   E. Make a narrow beam of light
   F. Disperse the light

5. The most important **observation** of a spectrum from an **energy saver globe** is that:
   A. I am not sure
   B. A full continuous spectrum is seen
   C. No light is emitted at all, it is all absorbed
   D. Only certain bands of coloured light are emitted
   E. Not sure

6. The most important **conclusion** from spectrum from an **energy saver globe** is that:
   A. I am not sure
   B. Energy is emitted over a wide range
   C. Emitted energy is discrete or quantized
   D. The wedge of CD absorbs specific wavelengths of light
   E. The slit prevents certain wavelengths of light from entering the mini spec

7. When a **red solution** is placed in front of the light source, it acts as a filter. In this case the observation using the mini spec is:
   A. I am not sure
   B. Only the red bands will be seen
   C. All bands of light appear red
   D. All bands besides the red bands will be seen

8. The best explanation for the above observation is that:
   A. I am not sure
   B. Red Light has low energy
   C. Red light is absorbed by the filter
   D. All other frequencies of light, besides red light, are absorbed by the filter

Please make sure all of your above answers are filled in on SIDE 2 of the pink optical sheet.

F: Post-Lab Questionnaire: Cycle 1 and 2

This questionnaire is part of a study to explore the benefits of using the Mini spec (Schwabacher, 1999). Participation in the study is voluntary. No marks are allocated for your responses, don't stress.

USE SIDE 2

Instructions

- You will need to complete a pre-prac and a post-prac questionnaire
- Do not fill in any of your details (name, surname, student number etc.). Your responses are anonymous.

Background information

1. Did you assemble the mini spec **yourself**?
   - A. Yes, I did it on my own completely / I needed very little help
   - B. No, I needed lots of help from my lab partners or tutor

2. How long did it take you to **assemble** the mini spec?
   - A. 0 – 5 mins
   - B. 5 – 10 mins
   - C. 10 – 15 mins
   - D. 15 – 20 mins
   - E. More than 20 mins
   - F. I was not successful at assembling the mini spec

Your Opinion

3. **Using** the mini spec was **easy**
   - A. I fully agree
   - B. I agree to some extent
   - C. I am not sure
   - D. I do not really agree
   - E. I definitely do not agree

4. I understand how this spectroscope works
   - A. I fully agree
   - B. I agree to some extent
   - C. I am not sure
   - D. I do not really agree
   - E. I definitely do not agree

5. This experiment helped me understand emission spectra
   - A. I fully agree
   - B. I agree to some extent
   - C. I am not sure
   - D. I do not really agree
   - E. I definitely do not agree

6. After this experiment, I feel confident for upcoming assessment in this topic
   A. I fully agree
   B. I agree to some extent
   C. I am not sure
   D. I do not really agree
   E. I definitely do not agree

7. I would recommend that the mini spec stays a part of CMY 133 for the future
   A. I fully agree
   B. I agree to some extent
   C. I am not sure
   D. I do not really agree
   E. I definitely do not agree

Conceptual questions

8. Which component of the mini spec acts as a prism?
   A. I am still not sure
   B. The shape of the mini spec
   C. The interior colour of the mini spec
   D. The wedge of CD

9. The purpose of the wedge of CD is to:
   A. I am still not sure
   B. Split light from the source
   C. Focus the light from the source
   D. Give the mini spec the correct shape
   E. Absorb unwanted wavelengths of light
   F. None of the above

10. The purpose of the slit is to:
   A. I am still not sure
   B. Block emitted light
   C. Dim the incoming light
   D. Protect your eyes
   E. Make a narrow beam of light
   F. Disperse the light

11. The interior (inside) colour of the mini spec is:
   A. Not important, any colour may be used
   B. Black
   C. White

12. Which of the following is **not** a function of the interior **colour** of the mini spec:
    A. Increase the brightness of the lines seen
    B. Increase the clarity of the lines seen
    C. Preventing internal reflectance
    D. Reducing stray light interference
    E. I am not sure

13. The most important **observation** of a spectrum from an **energy saver globe** is that:
    A. I am still not sure
    B. A full continuous spectrum is seen
    C. No light is emitted at all, it is all absorbed
    D. Only certain bands of coloured light are emitted

14. The most important **conclusion** from spectrum from an **energy saver globe** is that:
    A. I am still not sure
    B. Energy is emitted over a wide range
    C. Emitted energy is discrete or quantized
    D. The wedge of CD absorbs specific wavelengths of light
    E. The slit prevents certain wavelengths of light from entering the mini spectroscope

Please make sure all of your above answers are filled in on SIDE 2 of the pink optical sheet.

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15. Please fill in the comments section on this document if you have anything to say… For example, is there anything that you particularly enjoyed? Do you feel that some of the spectroscope prac was not useful? Do you have any tips or suggestions? *Or leave this section blank!*

Comments:

Thank you so much for your participation! You are helping us make CMY 133 better!

☺

G: Pre-Lab Questionnaire: Cycle 3, 4 and 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 jumps (replaced with 'drops' in cycle 5) 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.

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H: Post-Lab Questionnaire: Cycle 3, 4 and 5

Choose the option you feel is the most correct now that you have completed your laboratory experiment. Spectral lines are formed when:

A. An atom emits an electron to become more stable

B. An electron jumps (replaced with 'drops' in cycle 5) 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

Compare your current choice to your original choice. Motivate why you either kept or changed your answer.

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I: Collaborative Activity: Cycle 3, 4 and 5

1. The most important **observation** of a spectrum from an **energy saver globe** is that:

   A. I am not sure
   B. A full continuous spectrum is seen
   C. No light is emitted at all, it is all absorbed
   D. Only certain bands of coloured light are emitted

2. The most important **conclusion** from spectrum from an **energy saver globe** is that:

   F. I am still not sure
   G. Energy is emitted over a wide range
   H. Emitted energy is discrete or quantized
   I. The wedge of CD absorbs specific wavelengths of light
   J. The slit prevents certain wavelengths of light from entering the mini spec

3. As a group, which option do you consider correct? Spectral lines are formed when:

   A. An atom emits an electron to become more stable
   B. An electron jumps (replaced with 'drops' in cycle 5) 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

4. Discuss the four remaining options in Q3. To what extent do you agree with the options given? How could each of the options be changed so that the statement is correct?

J: Observation Checklist

Lecturer Observations

Research: MINI SPEC

Prac slot:	

1. Students' general technical ability at building and assembling the mini spec

2. Time range that the building and assembly took

3. Student mastery of holding the spectroscope to see the bands? Did they struggle? For how long? Were they eventually successful?

4. General time required for students to make the required observations of light using the mini spec.

5. Student engagement

6. Student enjoyment

7. Students discovering concepts: talking with their peers, trying to rationalise what they see

8. Do you as a lecturer feel this was a **successful experiment** in terms of
    1. Content
    2. Creating student interest
    3. Exposing students to procedures used in chemistry for analysis

9. Any other suggestions/ criticisms/ comments:

K: Analytic coding memos

7/8/2019 – Cycle 3

This was the first day of coding using Atlas.ti, I chose the CMY 154 Feb data (out-of-semester, cycle 3). I started with the three main barriers in mind: demands of the task, technical and non-technical words, and, conceptual difficulties. No evidence of the physical demands of the task manifested in the report sheet or pre/post lab transcripts. More codes have emerged than I expected.

"Prior knowledge" is the group of codes I made for students' core understanding of the function of the components of the spectroscope. This links to the demand of the task perhaps? The knowledge and application demonstrated by the students were coded as good, fair and poor.

8/8/2019 – Cycle 3

In going back to what the study has done, we added the missing macroscopic side of the triangle for emission lines, atomic structure, spectroscopy etc. Whether dealing with a triangle (Johnstone), a complex structure (Talanquer) or a continuum (Taber), the binding thread that enables and show cases learning is language. As noted by Rees, Kind and Newton (2019), language may be a barrier for students understanding. How that barrier manifests is different. Especially in a case like ours where "reflection" is used commonly by students to describe the function of the wedge of CD instead of "diffraction". There are three possible explanations for this:

1. The words sound similar in appearance and pronunciation, Ooyo 2004.
2. The words come from the same "word families" Rees et al., 2018, CERPP.
3. The meanings of the words are not well understood, students lack appropriate prior knowledge to distinguish between (or apply) the terms of "reflection" and "diffraction". This is perhaps the "language fluency" referred to by Rees et al 2019.

9/10/2019 – Cycle 4

The code set from 8/10/2019 had 22 codes. In this round of coding (9/10/2019), three codes were added dealing with the poor, partial and good understanding of the distinction between a continuous and a discrete spectrum. This has come into being because the refined wording of report sheet Q4 and options in Q3 have been designed to prompt student discourse in this distinction.

Language codes dealing with the term "jumps" have been redefined: one in which the term is considered in only an upward direction vs. a movement between levels.

I am concerned that there are too many codes and that they do not fit exactly with literature, especially quotation dealing with the code "reflection". It is so difficult to completely divorce language difficulties from conceptual difficulties and juggle the idea of prior knowledge and retrieval. Perhaps scientific fluency is the answer: to understand and recall a word and its meaning in a specific scientific context? The model of linguistic demands (Rees et al., 2019) leaves the cognitive aspect of mental models/schema out, along with omitting assimilation and accommodation, this a weakness of the linguistic demands model.

Definitions of scientific fluency

- Carambo 2011 thesis: "In these groups, the nature of their conversations as they used the science content to discuss their observations and solve problems evidenced a high degree of scientific fluency" (pp.174)

  "The use of tools, achieving of the goal (of the activity) and the quality of scientific discourse" (pp. 176)

- "The definition of general literacy and science-specific literacy are constantly being developed in response to changes in technological offerings and new literacies" "Instead of literacy supporting the acquisition of content, the two are co-dependent and can be leveraged to help students maximize their learning" (Powers and Kier 2016)

  "Students who are taught to be fluent in science will likely develop higher efficacy to act as a scientist and pursue more advanced, lab-based courses (Pearson, Moje, & Greenleaf, 2010)" in Powers and Kier (2016)

10/10/2019 – Cycle 4

At the start of today, there were 26 codes. The codes have been renamed in terms of topic and not level of understanding e.g. "Poor understanding of diffraction" has been renamed "Diffraction, poor understanding". This renaming makes code assigning easier as only three possibilities exist for diffraction, whereas multiple topics can be poorly understood.

10/10/2019 – Cycle 4

Perhaps students maintain the introductory physics concepts of refraction (the bending of light in a prism) and diffraction (the bending of light around and object)? Really a diffraction grating creates an opportunity for many instances of constructive and destructive interference of multiple diffracted light sources. So in essence, if OUR students say light splitting, diffracting or refracting (based on the prism analogy), it is correct. However, light is not merely reflected by the CD, the CD wedge has thousands of fine lines which act as a diffraction grating.

The code "quantization of light" is no longer useful as students tend to write about the nature of the light source and the continuity/ discrete nature of the spectrum. Quantization of light means that even though light is a wave, it nevertheless exists in discrete (distinct, countable and indivisible) units i.e. photons. By acknowledging a discrete spectrum, the student acknowledges the quantization of the electronic structure of the atom.

14/10/2019 – Cycle 4

"These authors define the construct of academic literacy as 'being able to use, manipulate, and control language and cognitive abilities for specific purposes and in specific contexts' (Van Dyk & Van de Poel, 2013:56). This view acknowledges that literacy practices are situated in specific contexts and cultures, yet still accepts that there are specific abilities (be they generic or subject-specific) that should be acquired for students to become academically literate" (From Fouche et al 2016).

15/10/2019 – Cycle 5

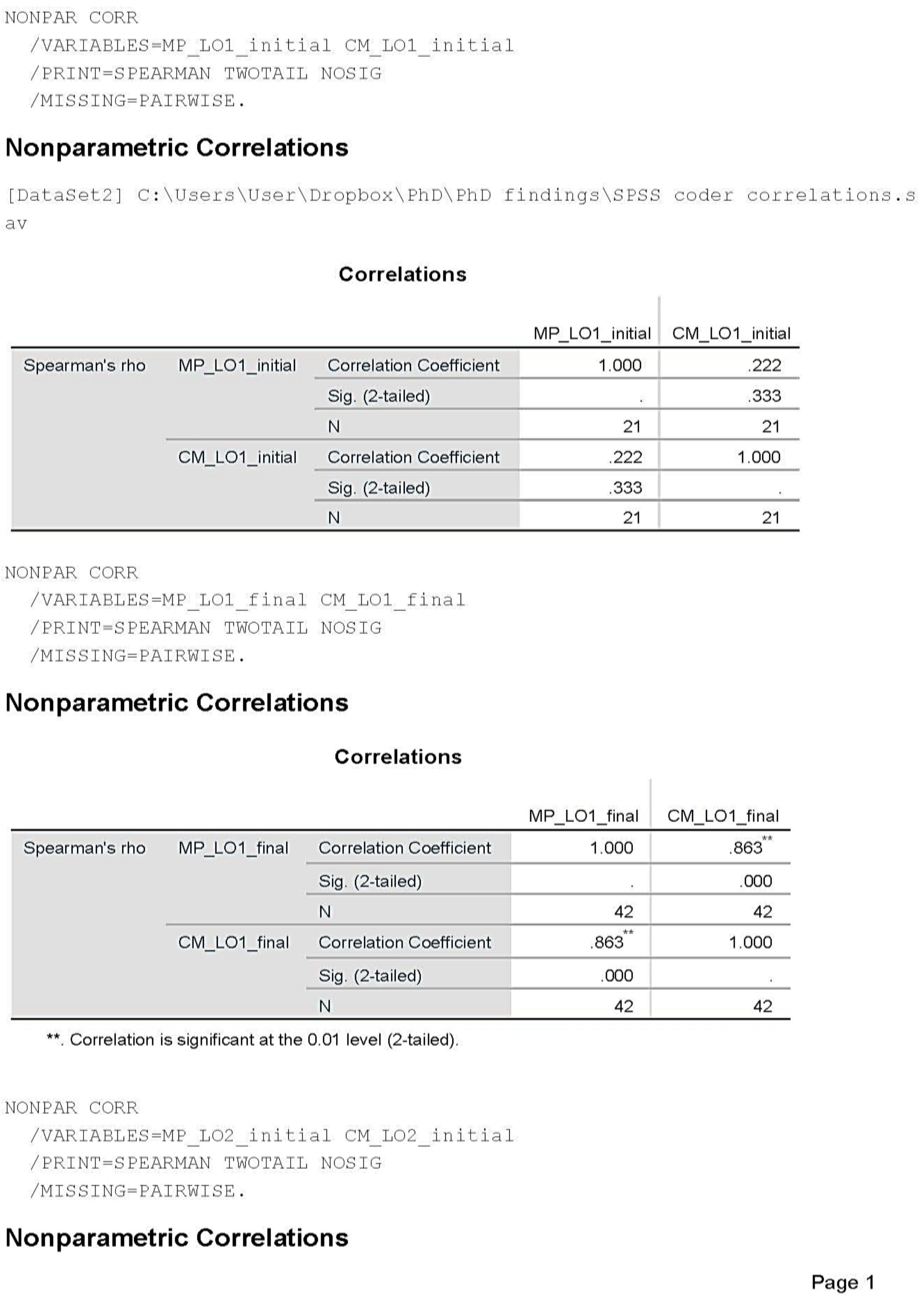
An understanding of spectral line intensity indicates a clear understanding of the two threshold concepts of "photon energy" and "electronic transition". What is unusual is that "all" (still need to verify this) students can predict the number of discrete emission lines (6 not 8) but fail to explain why some lines are more intense than others. The conceptual link should be the same: some transitions occur more frequently / have a higher probability than others, which is why 6 lines are counted instead of 8. But two of these lines should appear brighter because the transition has a higher probability of occurring!

The pre-lab activity number 2 was meant to refresh the mind of the student in terms of transitions and intensity. However, not all students get the final report sheet question correct. Could this be because not enough support was put into the pre-lab question, perhaps the addition of a sub question, "Which spectral line would appear brightest?" may help? A further sub-question "Explain why this is so." may further elicit student thinking

16/10/2019 – Cycle 5

Perhaps my coding has been too harsh in terms of the function of the CD: yes, the primary function in of the wedge of CD in a spectroscope is to act as a diffraction grating, to split light. The CD also reflects the light that hits it, but not before diffracting it, thus reflection may be seen as a secondary function of the spectroscope and should be classified as "partially correct" not "incorrect"? Defraction is also partially correct conceptually, as the direction of the light is changing. Refraction is not correct as light does not pass through different phases in the mini spec.

L: Inter-rater Reliability



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Nonparametric Correlations

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av
```

Correlations

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Spearman's rho	MP_LO1_initial	Correlation Coefficient	1.000	.222
		Sig. (2-tailed)	.	.333
		N	21	21
	CM_LO1_initial	Correlation Coefficient	.222	1.000
		Sig. (2-tailed)	.333	.
		N	21	21

```
NONPAR CORR
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  /PRINT=SPEARMAN TWOTAIL NOSIG
  /MISSING=PAIRWISE.
```

Nonparametric Correlations

Correlations

			MP_LO1_final	CM_LO1_final
Spearman's rho	MP_LO1_final	Correlation Coefficient	1.000	.863**
		Sig. (2-tailed)	.	.000
		N	42	42
	CM_LO1_final	Correlation Coefficient	.863**	1.000
		Sig. (2-tailed)	.000	.
		N	42	42

**. Correlation is significant at the 0.01 level (2-tailed).

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NONPAR CORR
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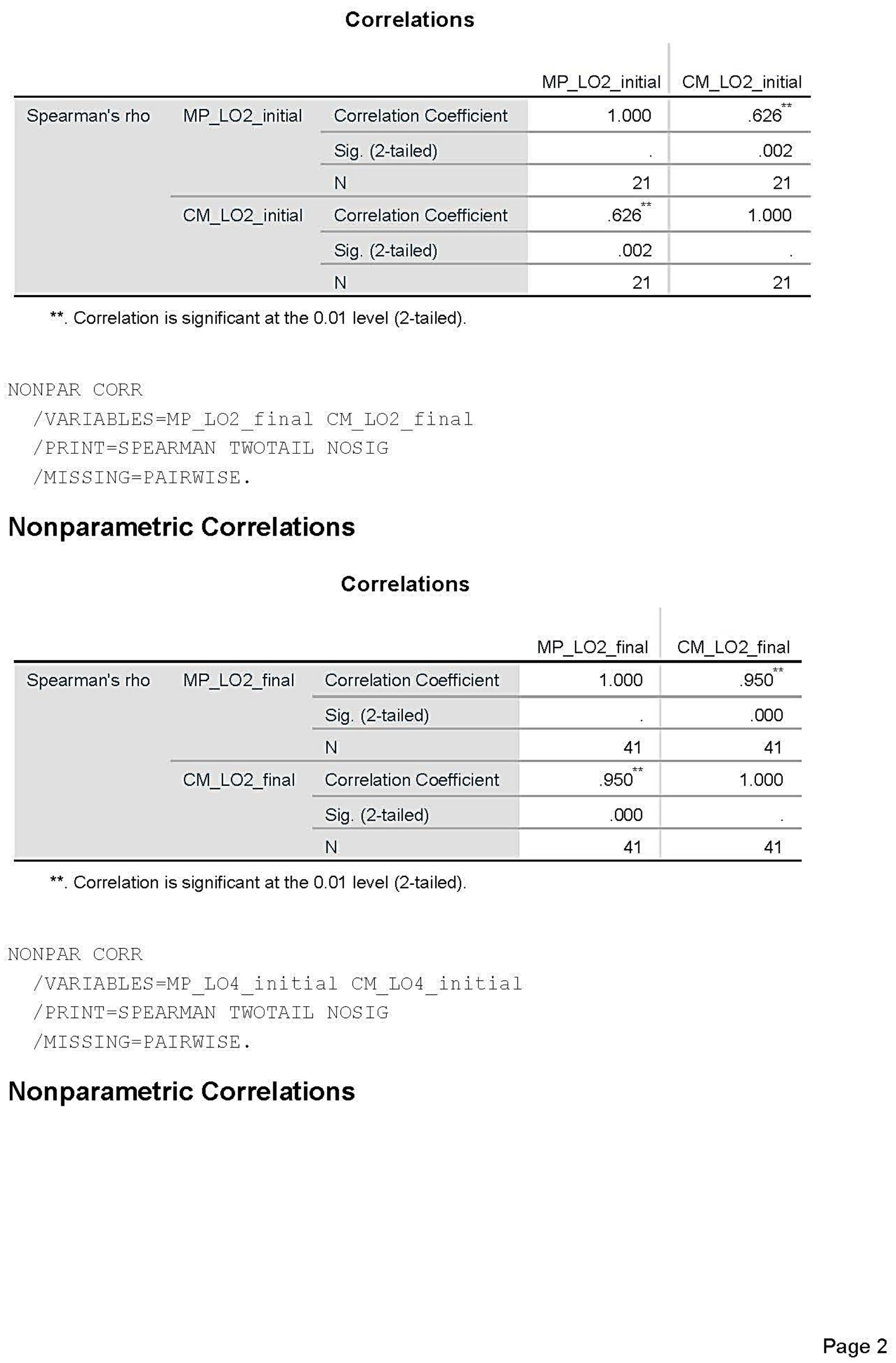
Nonparametric Correlations

Page 1



Correlations

			MP_LO2_initial	CM_LO2_initial
Spearman's rho	MP_LO2_initial	Correlation Coefficient	1.000	.626**
		Sig. (2-tailed)	.	.002
		N	21	21
	CM_LO2_initial	Correlation Coefficient	.626**	1.000
		Sig. (2-tailed)	.002	.
		N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

```
NONPAR CORR
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Nonparametric Correlations

Correlations

			MP_LO2_final	CM_LO2_final
Spearman's rho	MP_LO2_final	Correlation Coefficient	1.000	.950**
		Sig. (2-tailed)	.	.000
		N	41	41
	CM_LO2_final	Correlation Coefficient	.950**	1.000
		Sig. (2-tailed)	.000	.
		N	41	41

**. Correlation is significant at the 0.01 level (2-tailed).

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  /MISSING=PAIRWISE.
```

Nonparametric Correlations

Page 2

Correlations

			MP_LO4_initial	CM_LO4_initial
Spearman's rho	MP_LO4_initial	Correlation Coefficient	1.000	-.104
		Sig. (2-tailed)	.	.683
		N	18	18
	CM_LO4_initial	Correlation Coefficient	-.104	1.000
		Sig. (2-tailed)	.683	.
		N	18	18

```
NONPAR CORR
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  /MISSING=PAIRWISE.
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Nonparametric Correlations

Correlations

			MP_LO4_final	CM_LO4_final
Spearman's rho	MP_LO4_final	Correlation Coefficient	1.000	.839**
		Sig. (2-tailed)	.	.000
		N	34	34
	CM_LO4_final	Correlation Coefficient	.839**	1.000
		Sig. (2-tailed)	.000	.
		N	34	34

**. Correlation is significant at the 0.01 level (2-tailed).

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Nonparametric Correlations

Correlations

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Spearman's rho	MP_LO5_initial	Correlation Coefficient	1.000	.843**
		Sig. (2-tailed)	.	.000
		N	21	21
	CM_LO5_initial	Correlation Coefficient	.843**	1.000
		Sig. (2-tailed)	.000	.
		N	21	21

**. Correlation is significant at the 0.01 level (2-tailed).

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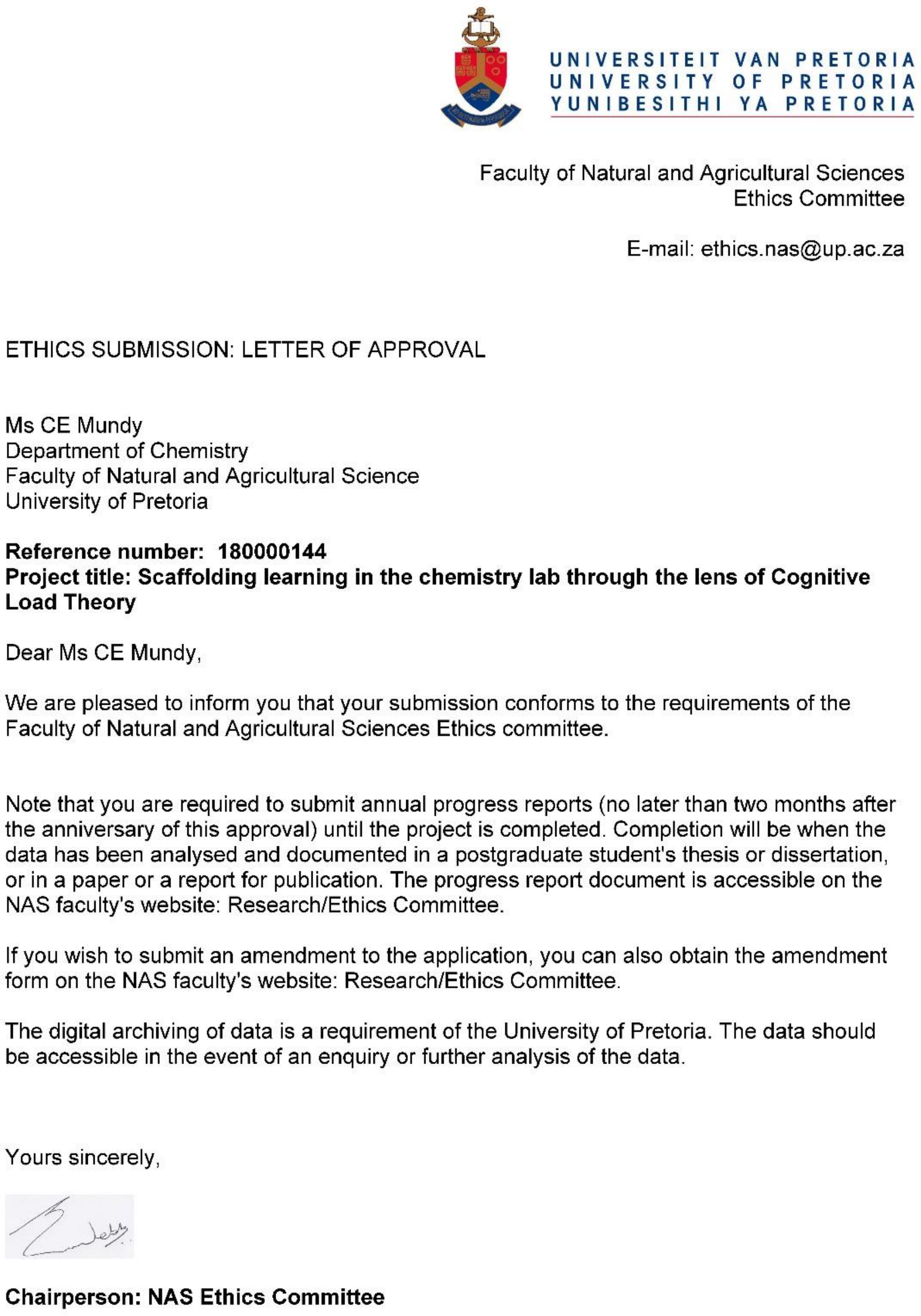
Nonparametric Correlations

Correlations

			MP_LO5_final	CM_LO5_final
Spearman's rho	MP_LO5_final	Correlation Coefficient	1.000	.950**
		Sig. (2-tailed)	.	.000
		N	42	42
	CM_LO5_final	Correlation Coefficient	.950**	1.000
		Sig. (2-tailed)	.000	.
		N	42	42

**. Correlation is significant at the 0.01 level (2-tailed).

M: Ethical clearance



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UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Natural and Agricultural Sciences
Ethics Committee

E-mail: ethics.nas@up.ac.za

ETHICS SUBMISSION: LETTER OF APPROVAL

Ms CE Mundy
Department of Chemistry
Faculty of Natural and Agricultural Science
University of Pretoria

Reference number: 180000144
Project title: Scaffolding learning in the chemistry lab through the lens of Cognitive Load Theory

Dear Ms CE Mundy,

We are pleased to inform you that your submission conforms to the requirements of the Faculty of Natural and Agricultural Sciences Ethics committee.

Note that you are required to submit annual progress reports (no later than two months after the anniversary of this approval) until the project is completed. Completion will be when the data has been analysed and documented in a postgraduate student's thesis or dissertation, or in a paper or a report for publication. The progress report document is accessible on the NAS faculty's website: Research/Ethics Committee.

If you wish to submit an amendment to the application, you can also obtain the amendment form on the NAS faculty's website: Research/Ethics Committee.

The digital archiving of data is a requirement of the University of Pretoria. The data should be accessible in the event of an enquiry or further analysis of the data.

Yours sincerely,

Chairperson: NAS Ethics Committee

N: Participant information

Ref: 180000144

PARTICIPANT INFORMATION

TITLE OF STUDY: Scaffolding learning in the chemistry lab through the lens of Cognitive Load Theory

1) Introduction

We invite you to take part in a research study. This information leaflet will help you to decide if you want to participate. Before you agree to take part you should fully understand what is involved. If you have any questions that this leaflet does not fully explain, please do not hesitate to ask the research personnel.

2) Why are we doing the study?

We would like to improve student learning gains in spectroscopy by analysing student reasoning. All students enrolled in CMY 133 may take part in this study.

3) What will we ask you to do in this study?

We will ask you to form a small group at the end of the lab session and discuss four questions together. This should not take longer than 30 minutes maximum. A voice recorder will be used. You will remain anonymous.

4) Risk and discomfort involved

We do not expect any risks or discomfort to the participants.

5) Possible benefits of the study

By thinking through your understanding of spectroscopy and reflecting on the lab experiment as a group, it is expected that you will solidify your learning. It also gives the researcher the opportunity to see how to further support learning in this topic for future first year students.

6) What are your rights as a participant?

Your participation in this study is entirely voluntary. You may choose not to answer particular questions. You can refuse to participate or stop at any time during the study without giving any reason. If you decide not to be in this research or if you decide to stop at a later date, there will be no penalty or loss of benefits to which you are entitled. Once you have completed the study you have the right to access your data.

7) Has the study received ethical approval?

This study has been submitted for approval from Research Ethics Committees of the Faculty of Natural and Agricultural Sciences, tel 012 420 4356.

8) Information and contact person

If you have any questions or comments about the study please contact Ms Christine Mundy on christine.mundy@up.ac.za

9) Confidentiality

All information that you give will be kept strictly confidential. Research reports, presentations and articles in scientific journals will not include any information that may identify you.

O: Consent form

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CONSENT TO PARTICIPATE IN THIS STUDY

I, ____ understand that:

1. The purpose of this study is to understand and improve the learning environment in the CMY 133 laboratory sessions.
2. The findings from this study will inform the design of laboratory materials.
3. I have had time to ask questions and have no objection to participate in the study.
4. As part of this study I have volunteered to participate in a group discussion which will be voice recorded.
5. My participation in this study will not influence the marks that I receive in this course.
6. Any personal information collected about me during this study will not be divulged in any written report, thesis or publication using the data from this study. Pseudonyms will be used when reporting data in written documents or presentations.
7. I am not waiving any human or legal rights by agreeing to participate in this study.
8. My participation in this study is completely voluntary. I have the right to withdraw at any stage, without prejudice.
9. The type of risk that may be associated with this study is discomfort. However, the researcher will strive to make me comfortable and address any concerns that I may have, during the course of this study.
10. If I have any questions about the research, during or after volunteering, I may direct my queries to Christine Mundy at Christine.mundy@up.ac.za or call 012 842 3531.

I verify that by signing below, that I have read and understand the conditions above:

Participant's name .... (Please print)

Participant's signature .... Date...............................

Investigator's name .... (Please print)

Investigator's signature .... Date...............................

Witness's Name .... (Please print)

Witness's signature .... Date...............................

P: Participant Index

Cycle 3 (n = 9)

2019

CMY 154 (out of semester)

Recordings: Groups 1, 2, 3

Participants: P33 – P41

Cycle 4 (n = 19)

2019

CMY 133 (in-semester)

Recordings: Groups 7, 8, 9, 10, 11

Participants: P42 – P60

Cycle 5 (n = 29)

2019

CMY 133 (in-semester)

Recordings: Groups 4, 5, 6, 12, 13, 14, 15, 16, 17, 18

Participants: P1 – P32; P1 – P8

Q: Raw Data

Staff observations

Staff observations (cycle 1)

Report sheet data

Link to scanned report sheets (cycle 3, 4, and 5)

Collaborative recordings

Link to collaborative audio recordings (cycle 3, 4 and 5)

Collaborative transcriptions

Link to collaborate transcriptions (cycle 3, 4 and 5)

R: Data programming

Programming for Fig. 21 (Full n=29)

http://sankeymatic.com/build/

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LO1 Poor [0] LO2 Partial
LO1 Poor [2] LO2 Good
LO1 Partial [0] LO2 Poor
LO1 Partial [7] LO2 Partial
LO1 Partial [9] LO2 Good
LO1 Good [1] LO2 Poor
LO1 Good [2] LO2 Partial
LO1 Good [8] LO2 Good

LO2 Poor [0] LO4 Poor
LO2 Poor [1] LO4 Partial
LO2 Poor [0] LO4 Good
LO2 Partial [4] LO4 Poor
LO2 Partial [3] LO4 Partial
LO2 Partial [2] LO4 Good
LO2 Good [0] LO4 Poor
LO2 Good [16] LO4 Partial
LO2 Good [3] LO4 Good

LO4 Poor [4] LO5 Poor
LO4 Poor [0] LO5 Partial
LO4 Poor [0] LO5 Good
LO4 Partial [12] LO5 Poor
LO4 Partial [3] LO5 Partial
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LO4 Good [2] LO5 Partial
LO4 Good [0] LO5 Good
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