Evaluation of an ‘open box’ undergraduate laboratory experiment for understanding how a UV-Vis spectrometer works

Master’s Thesis

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In this study, a novel 'open box' spectrometer experiment that was introduced in a first-year undergraduate chemistry laboratory course in Durham University in 2018 was evaluated with the aim to determine its success and further improvement of the experiment. The learning objectives of the experiment and their alignment with it was examined. Furthermore, the impact of the open box nature of the experiment on students in understanding how a UV-Vis spectrometer works and how the assessment determines the level of students' understanding was analysed.

The focus group method was used as a research method. The focus groups involved developers and demonstrators of the experiment and four undergraduate students. Transcripts of the focus groups were analysed thematically to identify emerging themes. Findings from the focus groups suggested that the novel approach of the experiment was considered positive, but improvements are needed to make the experiment more efficient. The learning objectives were not completely achieved because they were not communicated properly to students. There was also too much content in the experiment. The open box nature was found to aid students' understanding by enabling them to visualise the inside of a spectrometer, but the assessment should determine the level of students' understanding more precisely.

Keywords
chemistry teaching, open box spectrometer, UV-Vis spectroscopy, first-year undergraduate, hands-on learning, laboratory experiment, learning objectives, formative assessment

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2 Literature review

2.1 Introduction

In autumn 2018, a novel laboratory experiment for the first-year undergraduate laboratory course was put into operation in the Department of Chemistry of Durham University. This experiment was named *Construction of a UV-Vis Spectrometer*. The purpose of it was to increase students' *understanding on how a spectrometer works by building one yourself*.[1] The aim was intended to be achieved by constructing an 'open box' UV-Vis (ultraviolet – visible light) spectrometer utilizing Lego[*] bricks, using it for measuring an absorbance spectrum of potassium permanganate ($KMnO_4$) solution and processing the measurement data with MATLAB[†] and Microsoft Excel. The term 'open box' refers to the structure of the spectrometer: in comparison to a typical 'black box' spectrometer, in which the *internal structure is unknown to the user*, the components of an open box instrument can be viewed by the user.[2] In addition to the open box structure, another novel aspect of the experiment is that students are not provided with precise, step-by-step instructions for constructing the spectrometer. They are given a cardboard box, Lego bricks and other necessary components for building the instrument, and the order of components is given in the laboratory manual, but the fine adjustment of the components is not described in detail. Thus, by combining the use of Lego bricks, open box nature and non-traditional instruction style, students were intended to gain understanding about how a spectrometer works. A simplified schematic representation of the procedure of the experiment is presented in Figure 1.

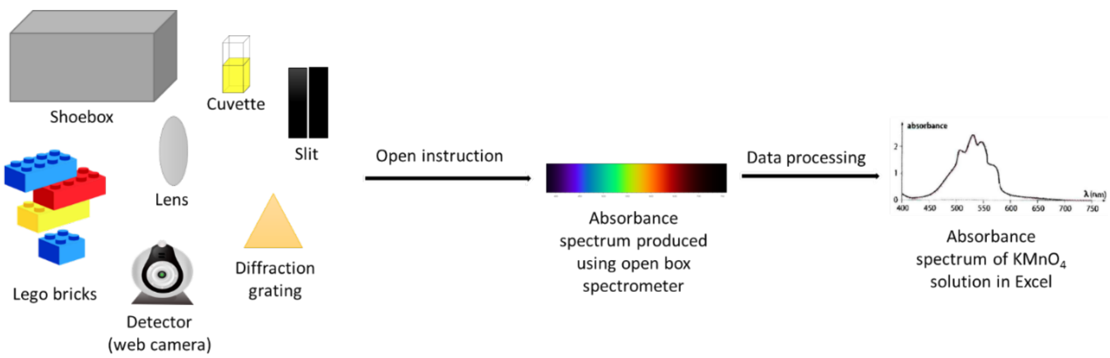

Figure 1. Simplified schematic representation of the procedure of the experiment. Images used in this figure are Creative Commons licensed.

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[*] Lego is a line of plastic construction toys that are manufactured by The Lego Group. Lego bricks are the flagship product of the company. (https://www.lego.com/en-fi accessed 6.5.2020)

[†] MATLAB is a computing environment and programming language. (https://se.mathworks.com/products/matlab.html accessed 15.5.2020)

When the experiment was carried out for the first time by students in 2018, the course leader noticed that the intended outcome was not always met. Students were reported to have struggled much more than they were expected to. To understand what should be changed in the implementation of the experiment, a thorough evaluation of the current experiment was needed. Therefore, the purpose of this study is to evaluate the experiment from a pedagogical perspective. The focus of this study is to identify the learning objectives of the experiment, how are they achieved by students, and if they are not achieved, why. The key concepts of this study are learning objectives, formative assessment and use of an open box spectrometer, which are further discussed in the following chapters. Defining the learning objectives is generally considered as a starting point for any kind of teaching, which is why they were found to be particularly important to examine when evaluating this experiment.[3] Assessment itself is strongly related to learning objectives, because learning objectives should guide decisions about assessment.[4] Among all the forms of assessment, formative assessment was of interest in this study, because the experiment was assessed formatively. Furthermore, an understanding of the intentions, means and outcomes of previously designed open box spectrometer experiments was found to be useful in evaluating this similar kind of experiment. Therefore, a short review of the previous studies on the field was conducted.

2.2 Learning objectives

The concept of learning objective is strongly linked to the planning, implementation and assessing of teaching, but it is a rather ambiguous concept. In some contexts, *objective* has been seen as synonymous with the terms *aim, goal, intent,* and *outcome*, while elsewhere, for example, a clear distinction has been made between the terms learning objectives and learning outcomes: learning objectives indicate what the teacher intends students to learn through their teaching, while learning outcomes describe what students are guaranteed to achieve as a result of teaching.[5,6] Over the decades, educational research has also sought to subdivide the concept of objectives into smaller, slightly differently defined sub-concepts, such as *educational*, *instructional* and *behavioural objectives*, and learning objectives have also been subordinated, in some contexts, to learning outcomes.[5] Furthermore, it has been suggested that the difference between learning objectives and learning outcomes is in the way they are written: learning objectives are statements about larger educational goals which cannot be directly measured or assessed, whereas learning outcomes are more specific and therefore measurable.[7] The definition that I use for learning objectives in this study is synonymous to the *educational objectives* defined by

Bloom et al. in 1981: they *describe in a relatively specific manner what a student should be able to do or produce, or what the characteristics are that the student should possess, after completing the unit or course*.[3] Thus, I consider learning objectives as statements of which are directly measurable.

Bloom et al. argue that *the role of education is to produce changes in learners*, but before changes can be stated as objectives, one has to decide which changes are possible and which are desirable.[3] The desired changes are communicated to students by a teacher or instructor in a form of learning objectives, but the teacher's decisions about desired changes are guided by many different parties, starting from the policy-makers of society, whose impact is reflected in the curriculum content, ending with the teacher's own experiences. In order to get the teacher's purposes communicated to students, learning objectives should be stated, and the statements need to be clear. [3–5] Stating the learning objectives clearly does not only make the communication between the teacher and students easier, but also helps the teacher. As Bloom et al. express, learning objectives *do provide a starting point and a frame of reference for planning how one will teach*, so the planning of teaching process should start with stating the learning objectives.[3] This inevitably pushes the teacher to consider the content of their teaching in depth and decide what they really want students to learn. Learning objectives also serve as a basis for choosing the teaching methods and assessment for the teacher.[4] It is seen as particularly important that the learning objectives align with both the practical implementation of teaching and the assessment in order to *generate powerful learning experience*.[8] When these three aspects are aligned, students have an opportunity to utilize learning objectives to guide their learning and monitor their progress; learning objectives can help students to self-assess.[4,9] Furthermore, evidence has been presented that clearly stated, realistic and assessment supporting learning objectives have a positive effect on both students' motivation, commitment and achievement of study goals.[10,11]

What does an effective learning objective, which maximizes the benefit of what both the teacher and the student can achieve, look like then? Bloom et al. argue that the appropriate 'instructional objective', interpreted here to mean the same as a learning objective, has two key characteristics: it defines the content of the learning situation and indicates what kind of change is expected to occur in the learner's behavior.[3] Ferguson, on the other hand, further subdivides the content part into smaller components, which are *audience*, *condition* and *degree.*[12] Audience defines who is the focus of the objective, condition states the conditions under which learning takes place, and the degree explains at what level learning is expected to happen. The fourth component presented by

Ferguson is behaviour, which implies the behaviour that indicates that learning has taken place. An example of such an objective following the ABCD structure (Audition, Behaviour, Condition, Degree) is presented by Ferguson:

> *Learners will identify the major muscles of the thigh with 100% accuracy when provided with a diagram.*[12]

Ambrose et al. present four characteristics for a good learning objective. They suggest that a clear and useful learning objective is student-centered, it breaks down the task into smaller parts and focuses only on a specific cognitive process, uses *action verbs* and is measurable.[4] Each of these criteria are also actualized in the presented example by Ferguson. The student-centeredness and measurability can be considered relatively obvious in this case but breaking down the task and the use of action verbs need some further explanations. A common problem is, according to Ambrose et al., that such complex skills as problem solving are considered as single skills by faculties, even though they actually *involve a synthesis of many component skills*.[4] Thus, if learning objectives require students to possess these complex skills directly, it may be difficult for students to perceive what they are actually expected to learn. Ferguson's example of a learning objective, however, clearly defines what students are intended to be able to do: *to identify the major muscles of the thigh*.

Action verbs refer to the Bloom's taxonomy, which is a widely used reference in research related to learning objectives.[4,5,7,9,13] Bloom's taxonomy of educational objectives classifies levels of competence according to cognitive processes, which are knowledge, comprehension, application, analysis, synthesis, and evaluation.[14] To describe each level of competence, Bloom lists a number of different verbs, *action verbs*, which Bloom et al. suggest to be used, among other things, to make learning objectives more precise.[3] For example, the verb 'identify' used by Ferguson is classified as a comprehension-level competence within Bloom's taxonomy. In contrast, a verb that is often used to describe competence, *to understand*, does not fall within the action verbs presented in Bloom's taxonomy, as 'to understand' is not a directly observable or measurable activity.[3] Because the action verbs presented in Bloom's taxonomy strive for clarity and unambiguity, favouring their use can be thought of as contributing to the achievement of learning objectives, such as communicating the teacher's aims to students.

2.3 Formative assessment

Assessment, at its narrowest, refers to the evaluation of learning outcomes, but it can be extended to include the evaluation of the teaching process, its inputs, outcomes and impacts.[15] There are many forms of assessment, but a clear division line can be drawn between diagnostic, summative and formative assessment. The purpose of the diagnostic assessment is to determine the student's knowledge and skill entry level, so it is carried out before the teaching period. Summative assessment aims to assess students' performance and competence at the end of a course or module and the assessment takes place afterwards. Formative assessment, on the other hand, takes place during a course or module and aims to motivate and guide the learner. [15,16] In this study, the focus is on formative assessment, as most of the assessment of first-year laboratory activities at the Department of Chemistry at Durham University is carried out in a formative way.

The concept of formative assessment has taken shape over the last fifty years, although, to some extent, its interpretation still varies to this day. The term *formative evaluation* was first used by Michael Scriven in 1967 for describing *the on-going improvement of the curriculum*.[17] In 1969, Benjamin Bloom suggested that the concept could be extended to the assessment of student learning, which, in practice, meant *to provide feedback and correctives at each stage in the teaching-learning process*.[18] What Scriven and Bloom's views on assessment had in common was that the information obtained would be used in one way or another to make changes. Indeed, Dylan Wiliam, who has done much research on formative assessment, regards making a change as a core of formative assessment: *an assessment of a student is formative if it shapes that student's learning*.[19] In other words, if assessment does not shape student's learning, it cannot be called formative. The term *assessment for learning* is sometimes used as a synonym for formative assessment, but Black et al. distinguish between these two terms precisely on the basis of whether the information gathered is utilized in practice.[20,21] They define assessment for learning as *any assessment for which the first priority in its design and practice is to serve the purpose of promoting students' learning*. Assessment for learning, according to Black et al., turns into formative assessment *when the evidence is actually used to adapt the teaching work to meet learning needs*.

Formative assessment can be further divided into formal and informal assessment.[22,23] Ruiz-Primo and Furtak describe that when formal formative assessment is implemented, students usually perform an activity which has been pre-planned or selected for them by the teacher to enable the teacher to gather information more precisely.[23] Shavelson et al. divide the forms of formative assessment into three different categories according to their formality.[22] They call the most formal of these as *embedded-in-the-curriculum formative assessment*, which includes goal-directed, ready-to-use assessment for teachers defined by curriculum developers. This kind of assessment they explain to *inform the teacher about what students currently know, and what they still need to learn*. A less formal form of this can be called *planned-for-interaction formative assessment*, in which the teacher plans the assessment herself or himself to match her or his own teaching.[22] By doing this, the teacher will get useful information about students' current level of knowledge, which allows teachers to direct their future teaching in the direction that is the most beneficial for students. Regarding the timing of the formal formative assessment, it should be noted that it is not precisely defined, but can be done before, during or after teaching.[23]

Informal formative assessment is continuous, more spontaneous than formal formative assessment, and can occur in all kinds of interactions between a teacher and a student.[23] Informal formative assessment can also be called *on-the-fly formative assessment* because of its spontaneous nature.[22] An example of a situation where a teacher conducts informal formative assessment is when a student's comment reveals an unexpected misconception in their thinking and the teacher responds in a way that seeks to help the student out of the misconception.[24] As such assessment is often induced by verbal questions and answers posed by students, the actions related are more immediate than with the formal assessment.[23] Ruiz-Primo and Furtak, whose research on informal formative assessment is focused especially on scientific inquiry, use the term *assessment conversation* for everyday dialogues between teacher and students. For the structure of the assessment conversation, they propose the so-called ESRU (Elicit, Student responds, Recognize, Use) cycle.[23,25] First, the teacher elicits a question, which the student responds to. The teacher recognizes the response and uses the information it provides to support the student's learning. Since this is a continuous cycle, it is thought that the use of information is again followed by a question from the teacher, which starts the cycle again from the beginning. There are many variations of the cycle in practical teaching situations, in which some stages of the cycle may be omitted or one stage may be dominant to other stages, but the study by Ruiz-Primo and Furtak suggests that the complete ESRU cycle is the one that provides the best learning outcomes.[25]

When dealing with formative assessment, special attention should also be paid to feedback, because the main purpose of formative assessment, as Mitchell points out, is to provide feedback; to the teacher on the one hand and to the learner on the other.[16] From the teacher's perspective, the feedback that formative assessment provides helps to understand the student's way of thinking and thus improve teaching, while from the student's perspective, formative feedback highlights the strengths and weaknesses of their performance and helps the learners to shape their actions in the future.[21,26] Certain guidelines have been presented in the literature for effective formative feedback. Mitchell suggests that feedback must be motivational, tolerate mistakes and not embarrass the learner.[16] Formative feedback is intended to answer three questions that can be asked by both teacher and student: *Where am I going?, How am I going? and Where to next?*[27] In his extensive review on the studies examining formative feedback, Shute gives guidelines for generating effective formative feedback.[28] He recommends that feedback should be focused on the task rather than the learner and their characteristics and effort, and that the feedback should contribute to the achievement of the intended learning goals. Furthermore, Shute states that feedback should be provided to students in small enough pieces, it should be simple enough, but still leave room for the learner's own thinking as well, and it should be clear and specific to the goals and performance. Things that Shute proposes to avoid with formative feedback are, for example, comparisons with other students, the use of hints that *always terminate with the correct answer*, and excessive use of praise as feedback. The sparing use of praise refers to the findings of Kluger and DeNisi in 1996, which suggest that praise can direct students' attention to their personality rather than the task or learning.[29] Finally, the necessity and conditions for formative feedback are summarised by Sadler in the following quote from his article on formative feedback and design of instructional systems:

> *Few physical, intellectual or social skills can be acquired satisfactorily simply through being told about them. Most require practice in a supportive environment which incorporates feedback loops. This usually includes a teacher who knows which skills are to be learned, and who can recognize and describe a fine performance, demonstrate a fine performance, and indicate how a poor performance can be improved.*[26]

2.4 Open box spectrometers

2.4.1 Overview of the field of study

Interest in developing novel, inexpensive absorbance spectrometers arose during the 1990s. At that time, it was noted that the instrumentation was getting more and more important in all fields of chemistry, but at the same time, the equipment was getting more expensive, which made it difficult for chemistry teaching laboratories to acquire enough instrumentation for teaching purposes at undergraduate level.[30] Therefore, efforts to lower the cost of absorbance spectrometers were made.[30,31] Although this early research did not directly aim at developing open-structured spectrometers, but rather focused on the inexpensiveness itself, it initiated the reform towards more student-friendly, easy-to-approach absorbance spectrometers.

In the beginning of 21st century, the pursuit of creating less costly spectrometers for undergraduate laboratories remained as one of the main purposes of the research in the area, but some new aspects gained ground as well. It was noticed that the instruments used in undergraduate chemistry laboratories tend to appear to students as 'black boxes', and the ability to use black box instruments may not require understanding how the instrument works.[32] Therefore, the open box spectrometers were needed. Also, a few studies suggested that if students could construct the low-cost spectrometers as a part of their laboratory work, it might enhance their understanding of spectroscopy and instrumentation itself.[33,34] At that time, the first spectrometer to utilize Lego bricks in its structure was introduced.[33] Since then, everyday objects (mostly Lego bricks, mobile phones and digital cameras) have been widely used as components of open box absorbance spectrometers. Primarily, everyday objects are favoured in the structure of the open box spectrometers because of their inexpensiveness, but the familiarity to students has also been considered beneficial for students' motivation. Furthermore, Lego bricks have been found to be useful as optical mounts because of the ease of use and the homogeneity of bricks.[33,35]

More work using actual open box spectrometers took place during the last decade. Several studies support the claim that the majority of commercial spectrometers have become so sophisticated and advanced that they are not very useful in teaching the basic principles of absorbance spectroscopy to students who have limited prior knowledge on the topic.[35,36] Therefore, various studies have focused exactly on developing DIY (Do-It-Yourself) spectrometers utilizing an open box nature to make the spectrometers easier for students to approach and understand.[33–35,37–40] In general, it can be stated that nearly all of the studies in this field of research during the 21st century have strived for lower costs and deeper understanding of spectroscopy by providing students with increased hands-on experience on using a spectrometer and by showing what is inside the instrument. The main features of previously developed open box absorbance spectrometers and the means and rationale of the experiments are presented in the following chapter.

2.4.2 Open box spectrometers in previous studies

The structure of an open box spectrometer is usually very simple, but some remarkable differences due to its simplicity occur. The basic components that all the absorbance spectrometers include are a light source, sample holder, dispersing element and detector.[41] An example of a very simple open box spectrometer, where only the aforementioned components are included, is the smartphone spectrometer introduced by Scheeline and Kelley.[34] In their experiment, the components (blue LED light, plastic cuvette, diffraction grating) are placed on a printed baseplate, and a smartphone, or alternatively a digital camera, is used for capturing the image of a spectrum. The image file is then imported to a specific software which is used for the data processing. The target group of their experiment is high-school and college students, and the learning objectives of the experiment are determined as follows:

- *List the components of a spectrophotometer and the order in which light traverses those components.*
- *Explain what a diffraction grating does, specifically including the concepts of dispersion and diffraction order.*
- *Explain what stray light is and explain how stray light decreases the quality of spectrophotometric measurement.*
- *Describe how a quality spectrophotometer would differ from the hand-made device.*[34]

The experiment is carried out by giving students *an open-ended guidance as to how they might build the spectrometer*. 'Open-ended guidance' can be considered synonymous with 'inquiry instruction', in which the procedure is student-generated and the outcome is undetermined.[42] The authors report that the experiment has been exceptionally successful in teaching the presented learning objectives, even though *there has been no controlled testing of student learning with the home-made spectrometer compared to other approaches*.

At the other extreme of complexity is an open box spectrometer introduced by Knagge and Raftery.[33] They designed a Lego spectrometer which is targeted to a graduate-level chemistry course. The spectrometer includes a light source, optical elements, such as a grating and a mirror for wavelength selection, sample holder made of Lego bricks, silicon photodetector and readout module. The base of the instrument is a flat Lego board and Lego bricks are used as optical mounts. However, the list of all the components needed for constructing the instrument includes fifteen different components, of which Lego bricks are one. Thus, the number of components of this spectrometer is three times as big as of the simple smartphone spectrometer introduced by Scheeline and Kelley. Furthermore, constructing the Lego spectrometer requires elaborate operations such as gluing the mirror to a flat Lego brick and setting up an amplifier circuit. The construction stage of it is not as straight-forward as with the smartphone spectrometer, where one just places the components as they are on a baseplate. On the other hand, no software is needed with the Lego spectrometer. The data is read straight from the display of a multi-meter. Knagge and Raftery do not determine the learning objectives as clearly as Scheeline and Kelley, but they believed that giving students hands-on experience in breaking a scientific instrument down to its components and reassembling it should teach students about *the electronic and optical modules important for its function*. However, the authors did not provide any further information about what students are supposed to learn in detail through the experiment.

In addition to selecting appropriate functional components to use in the spectrometer, the method used to block stray light from interrupting the measurements needs to be considered too. When using a spectrometer, the wavelength of light is intended to be controlled, but sometimes undesired wavelengths of light can appear inside the instrument. This kind of light is called stray light.[43] The main source of stray light in most of the commercially available spectrometers is the dispersing element in the monochromator, but when it comes to the open box spectrometers, the first priority is to prevent the light leaking in from outside of the instrument.[43] The most commonly used method to block stray light in open box spectrometers is to build the spectrometer into a cardboard box, such as shoebox.[33,35,38,40] Hosker, for example, designed a simple absorbance spectrometer, which was built inside a shoebox and a light sensor of a mobile phone was used as a detector.[40] The aim of the experiment was to *demonstrate the principles of diffraction, wavelength selection, calibration and light measurement, and absorbance calculation*. The main benefit of using a cardboard box is its inexpensiveness, but it has also a noticeable disadvantage. Grasse et al. found that even though cardboard box spectrometers *work nicely*, the repeatability of measurements is poor, because the structure is not stable enough.[37] To tackle the problem, the authors created a 3D printable plastic housing for components (a light source, slit, cuvette, mirror, diffraction grating and detector) to both stabilize the structure and to block the stray light. The spectrometer uses a smartphone as a detector and the instrument in its entirety is called *SpecPhone*[‡]. The authors suggested using SpecPhone for teaching such concepts as spectral resolution and Beer-Lambert Law. A similar type of stable spectrometer was also designed by Vanderveen et al.; a spectrometer which has a custom-built wooden frame in which the components are positioned.[39] In this design, called the *Littrow design*, the components which are placed inside the wooden frame are a slit, mirror, lens and diffraction grating. Once the wooden frame has been set up, these components are hidden inside and cannot be viewed anymore. However, the sample, light source and detector are positioned outside of the wooden frame and can be viewed at all stages. Neither the SpecPhone nor Littrow type spectrometer are actually called open box spectrometers by the authors, but they are considered open box spectrometers in this study as their components are visible for students at some stage of the experiment, whereas black box instruments hide the components at all stages.

Even though covering the spectrometer with a box is by far the most common option, it is not the only way to avoid stray light. The simple spectrometer design developed by Scheeline and Kelley, which was introduced earlier in this chapter, does not utilize any kind of housing around the components but the stray light is avoided by using the spectrometer in a darkened room.[34] Another study where an option for a sealable box is given, is introduced by Albert et al..[35] In this study, authors created a simplified version of the Lego spectrometer designed by Knagge and Raftery[33], targeting the spectrometer to first-year undergraduate students. The authors suggested two different ways for preventing stray light from reaching the detector: either covering the instrument with a shoebox or by positioning pieces of cardboard and walls made of Lego bricks to cover the detector and by dimming or turning off the room light at the same time. These options are presented as equal alternatives and it is not discussed in the study whether one is considered superior to another. Among all the studies reviewed here, this study is the only one that mentions the two different approaches to block stray light. Therefore, no actual discussion was found about whether closing the components inside a box temporarily or keeping the structure completely open is better for students' learning or whether it affects learning in the first place.

In addition to showing up the components of a spectrometer, most of the studies on open box spectrometers tend to highlight the DIY (Do-It-Yourself) nature of the experiment. Some studies suggest that breaking an instrument down to its components

‡ https://smithlab.uakron.edu/specphone/ (accessed 7.5.2020)

has a potential educational value in itself.[33,35,40] How it might increase student understanding, and what the specific skills and pieces of knowledge which can be learned through this action are, is, however, not often discussed in detail. Albert et al., for example, state that *allowing students to build their own spectrophotometer provides ample opportunity for teaching the underlying physical principles of spectrophotometry*, which is a conventional way of justifying the DIY approach in open box spectrometer experiments.[35] However, as this statement is not explained any further by the authors, it remains unclear how the authors believe the DIY nature would provide an opportunity for teaching or learning physical principles of spectrometry. A slightly more precise description was given by Grasse et al., who developed a 3D-printable SpecPhone spectrometer.[37] They state that interaction with the components provides students with a context for the parameters, which then assists in the development of *intuition for the relationship between the parameters and data collection*.[37]

The DIY nature is also utilized for improving problem-solving skills in open box spectrometer experiments.[38] Especially, this intention plays a central role in a project designed by Bougot-Robin et al., which is targeted to first-year undergraduate students.[38] The project consisted of eight laboratory sessions, and during those sessions students were supposed to design and build a spectrometer using Lego bricks, integrate it with a Raspberry Pi computer, optimize the spectrometer and finally use it for absorbance measurements and carry out kinetic studies. The learning objectives of the experiment are stated as follows:

> *1. Understanding the working principles of a UV-Vis spectrometer.*
>
> *2. Improve data handling and data processing by taking into account instrumental and sample limitations.*
>
> *3. Improve decision making especially when it comes to optimization.*
>
> *4. Improve problem solving ability.*
>
> *5. Finally, have some fun when designing and optimizing the spectrometers.*

These learning objectives were intended to be achieved by giving students open-ended instructions, instead of conventional, recipe-like instructions. The open-ended laboratory manual included all the necessary background information, from learning objectives to the theory of Beer-Lambert Law and diagrams and formulas related to the experiment, without still giving any step-by-step instructions. According to the authors, this approach was successful, and they reported that students enjoyed the experiment, learnt to troubleshoot and tackle errors, and furthered their understanding on the limitations of the instrument. At the end of the project, students wrote out a laboratory report, but the desired content of the report was not discussed in the study. Therefore, it is not clear how the project was finally assessed or how the level of the achievement of the learning objectives was measured.

As this review shows, there are numerous different aspects to consider when designing an open box spectrometer and the experiment where the instrument is to be used. All the open box spectrometers introduced here are designed to be inexpensive alternatives for the commercial black box instruments, and that is an undoubted benefit of all of them. Several studies emphasize the usefulness of open box spectrometers in teaching the key concepts of absorbance spectroscopy and the instrumentation itself, but no studies were found where any controlled testing on the learning outcomes of open box spectrometer experiments compared to traditional black box experiments had been conducted. Another deficiency of the previous studies is that many of them do not state the learning objectives clearly. However, two of the reviewed studies are more creditable than others in this sense; these are studies by Scheeline and Kelley and Bougot-Robin et al.[34,38] In addition to stating the learning objectives in a comprehensive way, these two studies are also the only open box spectrometer experiments to use open-ended guidance in the experiment. Furthermore, both studies reported that the students achieved most of the learning objectives. Even though these results are promising and might support the effectiveness of the approach that these studies took, more evidence on the effectiveness of specific decisions made in the designing process needs to be provided in order to draw accurate conclusions.

2.5 Summary

In the pedagogical literature, learning objectives are considered to be a central part of the planning and implementation of teaching.[3] Therefore, the way the learning objectives are stated does largely determine whether the teaching action is successful or not.[11] To find out whether the learning objectives are achieved, some form of assessment is needed. In order to measure the specific outcomes, the assessment needs to align with the defined learning objectives.[16] Formative assessment is one of the many forms of assessment, which can be a powerful tool in teaching, but it has several variations, and mastering the technique as a whole may require years of experience in teaching.[16,24] Only a few previous studies on open box spectrometers include a pedagogical approach towards the experiments, and therefore, the learning objectives and assessment is not widely discussed in those studies, even though some exceptions to this do exist.[34,38] However, in order to evaluate the experiments and their efficacy in teaching certain concepts to students, precisely determined learning objectives and the assessment of them are crucial.

3 Research questions

The purpose of my research is to evaluate the novel open box spectrometer experiment which has been part of the first-year undergraduate chemistry laboratory course in Durham University since autumn 2018. The evaluation is carried out by comparing the learning objectives to the practical implementation of the experiment, discovering the impact of the open box nature on students' learning and finding out how the experiment is assessed and how the assessment is supposed determine the level of students understanding of how a spectrometer works. The research questions are as follows:

1. *How does the current experiment align with the original learning objectives of the experiment?*
2. *How does the 'open box' nature of the experiment aid students in understanding how a spectrometer works?*
3. *How does the assessment of the experiment determine the level of students' understanding of how a spectrometer works?*

4 Methodology

The research data was collected through focus group discussions with the developers of the experiment, postgraduate students who acted as demonstrators of this experiment during last two autumns and first-year chemistry students who carried out the experiment in autumn 2019. The interviews were semi-structured and utilised a focus group method, where each of the three groups mentioned above formed their own focus group. The interviews were transcribed using the UK Transcription service and the transcripts were analysed thematically using an inductive approach. Frequent themes were searched from the data of each focus group, and the answers to research questions were sought by comparing these themes across different focus groups. Details of both focus group method and thematic analysis are explained in the following sub-chapters. The study received ethical approval from the School of Education Ethics Committee at Durham

University. Ethical approval was granted on 02/12/19. The participants gave their agreement to participate voluntarily in the study and were assured that their responses would be treated anonymously. The legal basis for collecting data for this study is Article 6(1)(e): Public Task.

4.1 Focus groups

According to Bryman, *the focus group method is a form of group interview in which there are several participants (in addition to the moderator/facilitator); there is an emphasis in the questioning on a particular fairly tightly defined topic; and the accent is upon interaction within the group and the joint construction of meaning.*[44] Another important characteristic of the focus group method is that those persons who take part in the discussion have to have been involved in a particular situation, such as the same laboratory experiment.[45] In this study, the focus groups (developers, demonstrators and students) were easy to form as there were three separate groups of people related to this experiment from the very beginning. The focus group method was found suitable for this particular study for several reasons. In general, using focus group technique, the researcher learns *why* the interviewee thinks in the way he or she thinks, which in this study was at least as important as *what* the interviewee thinks.[44] According to Bryman, listening to other participants' responses may make the individual rethink or deepen their understanding perhaps closer to the real reasons why things are perceived in a particular way. Even though this was a case study that did not seek to generalise the results in the broader picture, the aim was to obtain more than just random individuals' opinions on the work, which might have been a problem if individual interviews were chosen to be carried out instead of focus group discussions. In this sense too, the focus group method was well-suited to its purpose, as it provides a specific view of individuals' collective experience of the experiment, allowing for a more valid assessment of the whole.[44]

The sizes of focus groups were between two and four participants. With the developers and demonstrators, the selection of participants was straightforward: there were only four people involved in the developing process and two persons had demonstrated the experiment so far, which meant that they all were selected as participants and sizes of those groups did not need to be considered. However, the size of the last focus group, which was the focus group of students, had to be considered carefully as the number of first-year chemistry students is much larger than the practicable size of a focus group. Finally, the group size of four was chosen, due to its alignment with the developer focus group. The recommended minimum size for a focus group varies between three and six participants, and most of the focus groups of this study fall within this range.[46–48] The use of smaller group sizes has also been recommended in the literature. Studies show that in larger groups it is more difficult for the moderator to comment on the responses of individual participants, and also identifying multiple speakers during the transcribing phase can be challenging if there are too many participants.[49] Smaller groups, are generally stated to 'run more smoothly' and, in addition, the smaller groups provide a better ground for disagreement and differing opinions as the participants get more opportunities to have their say.[44,50]

Participants were recruited primarily via email. They were also provided with the necessary documents as attachments to the e-mail, which participants were asked to read before the focus group. These documents were a participant information sheet, a participation agreement form, a privacy notice and a copy of the laboratory manual. The email recruitment worked well for developers and demonstrators but failed for students. All the first-year chemistry students were sent an email invitation to participate in the study, but none responded. Thus, the decision was made that students would be recruited spontaneously during their lab session. According to the original plan, the sampling strategy that was to be followed was *extreme case sampling*. In extreme case sampling the cases studied are very information-rich, because they represent some kind of extremity in the studied group, and are believed to act as fruitful source of data for this reason.[46] In this case, the aim was to select students who were particularly active and enthusiastic in the laboratory course as they were thought to have more enlightened ideas about the experiment. However, as the original recruiting method was not successful, the sampling approach had to be changed too. The new sampling strategy was *purposeful random sampling*, whereby participants are randomly selected from a particular group.[46] In this case, that group was first-year chemistry students who had carried out the experiment. Because all the students in the laboratory at the time of recruitment met this condition, the first four volunteers were selected to participate in the study. The gender of students was not taken into account when selecting the volunteers as this was not expected to be relevant to the research. In general, no data other than the name and e-mail address were collected from participants in this study.

Focus group sessions were arranged in early 2020 at the facilities of the Department of Chemistry and the Teaching and Learning Centre of Durham University. The original plan was to arrange the sessions by the end of 2019, but this turned out to be impossible as the study did not get ethical approval until December 2019. The potential side effect of this was that demonstrators' and students' recollection of the experiment might have deteriorated over time as the experiment was already carried out in early December. However, no evidence of this was noticed in the discussions. The duration of the interviews varied between half an hour and an hour, depending on the focus group. At the beginning of the focus groups, the participants signed and returned the participation agreement forms, in which the participants confirmed that they had read and understood the documents sent to them, and gave their written consent to participate in the study. Also, the participation agreements included the pseudonyms of participants, which were to be used in the transcripts, in the data analysis and in the final report to avoid using their own names. An example of a used pseudonym is *Developer 1*. The focus group discussions were semi-structured: five to seven questions were prepared in advance for each focus group, but the participants' answers were also allowed to influence the course of the interview. The questions dealt with the practical implementation, assessment and learning content of the experiment in slightly different ways depending on the group. These questions are presented in Figure 2.

Developer focus group

1) What was your role in the designing process of this experiment?
2) How would you describe the designing process – which kind of steps did it include?
3) What are the main learning objectives of this experiment? Why?
4) This experiment is said to be assessed formatively. What made you to choose formative assessment before summative?
5) How are the demonstrators prepared for the assessment of this experiment? Do they know the exact learning objectives and how to assess them?
6) Which kind of other choices did you make during the designing process, excluding the learning objectives and assessment? Why did you make these choices?
7) What are the strengths and weaknesses of this experiment? Argue your choices.

Demonstrator focus group

1) This experiment is assessed by demonstrators. How do you carry out the assessment in practice? How are you advised to do the assessment?
2) Do you find it difficult to assess this experiment? How familiar you are with formative assessment?
3) What are the learning objectives of this experiment?
4) Do you agree with the learning objectives that the developers suggested?
5) Do you think the assessment aligns with the learning objectives of this experiment? In other words, are you assessing the same things that students are supposed to learn from the experiment?
6) How did the students manage this experiment in general? Did they struggle at some point? What may have been the reason for struggling?
7) What are the strengths and weaknesses of this experiment? Argue your choices.

Student focus group

1) How did you feel about this experiment? Was it easy or difficult or something in between? Which part of the experiment was the most difficult one and why?
2) Based on your experience, what was this experiment supposed to teach you?
3) After seeing the learning objectives set by the developers of this experiment, do you think you achieved these objectives?
4) Spectrometers are often used as "black box" instruments in laboratory experiments. However, in this case you constructed and modified the spectrometer by your own. Did this make it easier for you to understand how spectrometer works?
5) Did this experiment increase your understanding of how spectrometer works (remarkably / a bit / not at all)?

Figure 2. The questions discussed in the focus groups.

The general procedure of the focus groups was that the moderator asked the participants a question which they first answered from their own perspective and then the topic was discussed together in an informal way. When necessary, the moderator asked the participants some further questions arisen from the discussion. The moderator's role was, above all, to keep the discussion going and ask more specific questions, but to avoid expressing too much of one's own opinions in order to not to influence the participants' responses. The focus group discussions were audio-recorded with the Rode Podcaster microphone using Microsoft Sound Recorder software. Because there was an uncertainty about the operability of the microphone, the interviews were also recorded using the Android Recorder software as a back-up, which was explicitly requested at the beginning of the interview. After the interview, both audio files were transferred to Durham University OneDrive and removed from other locations.

4.2 Thematic analysis

Before the actual thematic analysis was started, the raw data, that is, the audio files of the focus groups, were converted into DOCX format text files. In this case, transcribing of the audio files was carried out using UK Transcription service, which is a commercial online transcription service. It is generally recommended that the researcher transcribes the interviews, because this can help the researcher to become familiar with the data.[44] However, despite being aware of this fact, it was concluded that because the researcher's mother language is different to the language used in focus group discussions, transcribing would have been immoderately time-consuming for the researcher. Thus, the use of an external transcriptionist was deemed necessary. All audio files were sent to the UK Transcription Service for transcription at the same time after the last focus group was completed. However, the audio recordings were also listened to between the focus groups in order to utilize some of the information gained in the later focus groups. Especially, the learning objectives defined by developers were needed in demonstrator and student focus groups.

The method that was selected for analysing qualitative data in this study was thematic analysis. Thematic analysis is one of the most common approaches in qualitative data analysis, and it has much in common with grounded theory, which, however, is much more precisely defined as a method than thematic analysis.[44] As Braun and Clarke state, *thematic analysis is a method for identifying, analysing and reporting patterns (themes) within data*.[51] Thematizing meanings, which is one of the key points of thematic analysis, is also one of the skills that most of the qualitative analysis methods have in common, which makes thematic analysis an important technique for qualitative researcher to master.[52] However, the significant difference between thematic analysis and other methods of qualitative analysis lies in the fact that it is not firmly bound to any theoretical framework and that there are no precise guidelines for its practical implementation.[51] Flexibility of the method was the main reason why thematic analysis was used in this study: because the open box spectrometer experiment had not been studied earlier from the chosen point of view and it was not known exactly what to expect from the data, it was preferred to leave as much leeway to the analysis part as possible. On the other hand, as Braun and Clarke point out, thematic analysis can also provide a more accessible approach to qualitative analysis, especially for inexperienced qualitative researchers, so the method was also considered particularly well suited for this purpose.[51]

Thematic analysis is divided into inductive and deductive approaches.[51] In inductive approach, themes are determined by data, rather than the researcher deciding what themes to look for in the data before collecting and analysing it.[46] The deductive, or theoretical, approach is linked to the researcher's own theoretical or analytical interests.[51] Braun and Clarke further explain that the researcher who chooses a deductive way *might approach data with specific questions that you wish to code around*. In this study, I decided to use the deductive approach. In practice, this meant that once the material was coded, the codes were grouped by the categories determined by research questions. These categories were named 'open-box nature', 'assessment' and 'learning objectives'. In addition, a fourth category was created, and it was named as 'general design'. Codes classified to 'general design' category were those that could not be classified to any other category. This category was finally then divided into two new categories, which were 'the rationale for the design' and 'difficulties'. In the *Results and discussion*, however, these are presented under the research question *1. How does the current experiment align with the original learning objectives of the experiment?*

Before the actual analysis took place, the 'level' of the themes to be searched for had to be decided. By Boyatzis' definition, the level of themes can be either semantic (manifest) or latent.[53] At the semantic level, *the themes are identified within the explicit or surface meanings of the data, and the analyst is not looking for anything beyond what a participant has said or what has been written*.[53] By contrast, at the latent level, the ideas and ideologies beyond spoken or written thoughts are of interest.[51] Due to the practicality of the research questions used, it was decided to address the themes at a semantic level in this study.

In the thematic analysis, a procedure presented by Braun and Clarke was followed.[51] This procedure is also presented in Bryman's *Social Research Methods* and has been used by other researchers.[44,54,55] The procedure consists of six steps, which are presented below:

1. *Familiarizing yourself with your data*
2. *Generating initial codes*
3. *Searching for themes*
4. *Reviewing themes*
5. *Defining and naming themes*
6. *Producing the report*[51]

In many cases, the familiarizing phase begins with transcribing, but in this case, as the transcribing was not done by the researcher, analysis began by reading through the transcripts. The total of pages of transcripts was 83. To ensure consistency between the original audio files and the transcripts, the transcripts were also read while listening to the corresponding audio files simultaneously, as Braun and Clarke recommend to always do with transcripts.[51] At this point, some marginal corrections were made to those parts of transcripts that were incongruent with audio files. When the transcripts were read for the third time, the main content of the interviews was written on post-it notes, which were stuck to the printed transcripts at the respective places. The notes contained both direct quotes and summaries of the participants' thoughts. Based on these notes, initial codes began to be formed, which were more concise and more commonly formulated expressions than those in the original notes. According to Boyatzis, codes represent *the most basic segment, or element, of raw data or information that can be evaluated in a meaningful way regarding the phenomenon*.[53] Initial codes were also written on post-it notes which were appended to the original notes. An example of how a note was formed from a data extract and how it was edited into an initial code is presented in Table 1.

Table 1. An example of how notes and initial codes were formed out of data extract.

Data extract	Note	Initial code
So it was about, 'Everybody in the year needs the opportunity to see inside a spectrometer.' So the designing process was starting from that, really. It was established, from the physical section, that that was a gap that was needed to be filled. (Developer 1, developer focus group)	Every student needs to see inside a spectrometer.	Need to see inside.

For the following steps, it was desired to convert all the data to electronic form. The raw data was transferred to Microsoft Excel and manipulated utilising the guidelines for using

Excel in thematic analysis published by Bree and Gallagher.[54] The data from each focus group was separated into their own tables. The raw data contained the original notes from each focus group, the related direct quotes and the pseudonyms of the quoted participants. The number of notes was 171 at this point. Next, the notes were colour-coded into four different categories, which were determined by the research questions. Some notes were considered to belong to more than one category, and those rows were duplicated in Excel and colour-coded to as many categories as needed. At this point, the notes were still kept in chronological order and each focus group in their own table. At this point, the total number of rows was 204. Altogether, the analysis conducted in Excel consisted of eight different rounds of iterations, which included condensing, re-grouping and re-coding of the data to formulate the broader themes, which were further reviewed and compared to the raw data in order to ensure the accuracy of the themes. Finally, the thematic analysis resulted in 23 different themes under five categories.

5 Results and discussion

Results of thematic analysis and the discussion related to the results are combined in this chapter. They are presented by research questions, which are: *1. How does the current experiment align with the original learning objectives of the experiment? 2. How does the 'open box' nature of the experiment aid students in understanding how a spectrometer works? and 3. How does the assessment of the experiment determine the level of students' understanding of how a spectrometer works?*

Each chapter ends with an overview which highlights the most important findings related to that research question, suggests answers to the research question and widens the discussion to the relevant literature.

5.1 How does the current experiment align with the original learning objectives of the experiment?

5.1.1 Characteristics of the experiment defined by the developers

At the start of the focus group, the developers were asked about the steps of the designing process. They described that the process began with their observation, that even though the first-year laboratory course had been supplemented with analytical experiments for the last four or five years, none of them dealt with the instrumentation itself. Furthermore, developers had noticed that students do not know in general what processes and phenomena occur inside a spectrometer. For these reasons, developers wanted to have an experiment where students could see inside a spectrometer:

> *So, it was about, 'Everybody in the year needs the opportunity to see inside a spectrometer.' So the designing process was starting from that, really. It was established, from the physical section, that that was a gap that was needed to be filled. (Developer 1, developer focus group)*

The *Spectroscopy in a Suitcase* project by The Royal Society of Chemistry, which sought to bring spectroscopy equipment into schools, was also said to have inspired the developers in creating the experiment. When the gap in the content of the laboratory course was identified, developers had to decide which field of spectroscopy the experiment should deal with. As it was to be in the first-year laboratory course, the experiment could not be too complex, which led the developers to choose a spectrometer that functions in the visible range of light. A Vis spectrometer was said to be *the easiest one to develop, because you can see the visible spectrum (Developer 2, developer focus group)*. The developer explained this to refer to, for example, an IR spectrometer being significantly more expensive to develop, because the equipment needed for detection of IR radiation is more complex and thus more expensive than those required for measuring visible light. Indeed, 'inexpensiveness' was one of those themes which affected the design remarkably and which was mentioned several times in the developer focus group. The need for reducing costs was reported to be particularly great for the first-year laboratory course, as there are numerous students completing it but only limited resources available.

In terms of practical implementation, two key themes were evident from the data: developers wanted the Lego bricks to be utilised in the structure of the instrument and students were desired to construct the spectrometer on their own. Demonstrators had recognised that spectroscopy experiments are sometimes very tedious for students, hence Lego bricks and the DIY nature were included in order to create something more fun than usual. A developer compared the use of a typical spectrometer to a Lego spectrometer as follows:

> *They put in a sample, and then they sit there with a stopwatch [in typical spectroscopy experiments]. What I'd really like to do is, why not build a spectrometer? They could do this so much better with my Lego spectrometer. Build the spectrometer, and then actually interface their output. (Developer 3, developer focus group)*

Developers had become familiar with using Lego bricks in spectrometers by exploring previous studies on the topic. Lego bricks were found to be useful because they are *easy to manipulate*, *versatile* and *accurate*. Another feature of Lego, which was said to be useful, was its familiarity to students. The developers believed that the familiarity of Lego would make the experiment easier to approach.

> *Everyone knows Lego. Everyone knows how to play with Lego, so it's a sense of comfort for the students. -- So it's supposed to give some confidence. (Developer 3, developer focus group)*

The DIY nature, which is not an inseparable part of open box instrument experiments, but which fits well together with them, was not only thought to make working more fun for students but was also considered an integral part of the learning process. As Developer 3 pointed out, *students tend to learn by doing, rather than sitting in a lecture*, and what they wished for was that learning by doing would lead to deeper understanding, instead of memorising. This was discussed by a developer as follows:

> *What I think all of us would really like our students to be able to do is not to memorise equations like the Beer-Lambert Law. We can memorise the overall structure that there's a law of something over something. But if you've done the experiment, as you were saying, you know you're measuring absorbance as a change in transmission. (Developer 3, developer focus group)*

To support the idea of learning by doing, the instructions for constructing the spectrometer were left more open than typical, recipe-like laboratory instructions. The aim was that the students would not be able to complete the construction part by simply following the instructions, but they would end up, through trial and error, finding a suitable structure for the spectrometer on their own. The instructions were described by a developer to be *open-ended to some extent* as there were several possible alternatives for the final structure of the spectrometer. However, for the data processing part, students were provided with very detailed instructions to follow, so the open-endedness did not follow through the whole instructions.

Although the developers wanted to make the experiment more interesting for students than spectroscopy experiments tend to be, it was not intended to be mere play: at the same time, developers also wanted the students to produce data and to learn how to process it. As Developer 3 stated, *one of the key points of the experiment is that it is* *quantitative.* A summary of the characteristics that the developers desired to be combined in the experiment are presented in Figure 3.

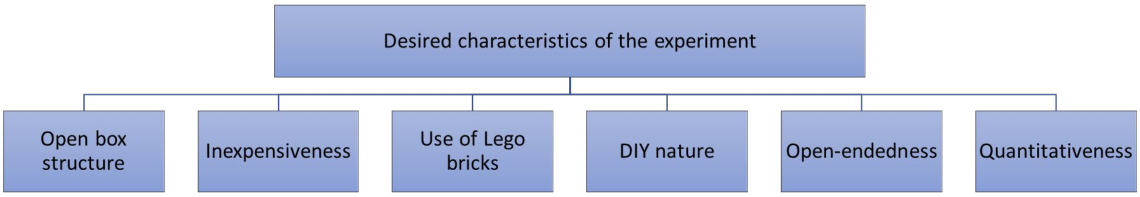

Figure 3. Summary of the desired characteristics of the experiment defined by the developers.

5.1.2 Developers' perspective on learning objectives

Developers' perspective on the learning objectives of the experiment was sorted out by comparing two different sources: the student laboratory manual and the focus group discussion with developers. In the introduction section of the student laboratory manual, it is stated that *the aim of this experiment is to understand how a spectrometer works by building one yourself.*[1] This can be considered as a learning objective of this experiment. In addition, a list of *key outcomes* is presented as part of the instructions. The list includes five bullet points which explain the content of the experiment. These key outcomes are listed in the laboratory manual as follows:

> *After completing this experiment, you should have:*
>
> - *Designed, built and modified a spectrometer that can produce an absorbance spectrum for potassium permanganate solution in the visible light range.*
> - *Used the spectrometer to collect data of a good standard and made adjustments to the design to improve the quality of your data.*
> - *Converted raw data into an appropriate and usable data array using computational techniques in MATLAB.*
> - *Calibrated the spectrometer using Solver in Excel.*
> - *Used your understanding of light and spectroscopy to critically discuss your experimental results and compare them to literature results.*[1]

However, these are not considered as learning objectives, because they don't fulfil the criteria of learning objectives used in this study: they describe what a student does *during the experiment*, rather than what a student is able to do or produce *after completing* it, which is a fundamental part of the concept.[3] In other words, it is not clear whether students are intended to learn these features as a result of this experiment or whether these actions are carried out in order to learn something else through them. Even though they could be modified into a form of appropriate learning objectives, they are not regarded as learning objectives for the aforementioned reason.

When developers were asked to specify the learning objectives of this experiment, several different aims and objectives for students' learning were mentioned. Some of them related to general qualities that students need in their chemistry studies, while the rest of them dealt specifically with spectroscopy. I named one of the themes that emerged the most as 'research skills' and it included such sub-themes as 'independent working', 'troubleshooting', 'problem-solving' and 'decision-making'. Developers themselves did not use the phrase 'research skills', but it was considered to be a suitable phrase to describe these sub-themes. Thus, all these abilities classified as research skills were something that developers wanted the students to learn through this experiment. However, these abilities were discussed only by half of the developer group. Developer 1 explained why these specific learning objectives are covered by emphasising the open-ended nature of the experiment and comparing it to the *recipe-driven* experiments, of which the main point is to teach students the *process and procedure*:

> *But what they actually need -- for the open-ended exercise, is the ability to troubleshoot, the ability to problem-solve, and actually, the ability to tackle a problem that has no one correct answer, where there are some possible outcomes that will work, and that there are some answers. So there is no one predetermined point to get to. (Developer 1, developer focus group)*

Another learning objective highlighted several times by developers was 'to gain confidence in the laboratory'. This theme was discussed by all the developers during the focus group, so the importance of it was clear. Increasing confidence in the laboratory was found particularly important for those who have just completed A-levels, as a developer's response indicates:

> *It gives the students confidence in the lab, and they can play. Because ultimately, the students come in from A-Level chemistry*

> *with a lack of confidence in a laboratory environment. But by giving them a pile of LEGO and saying, 'Play with it. You're not going to break it. You're not going to damage anything,' they've got an opportunity to explore things. (Developer 2, developer focus group)*

On the other hand, the developers were also aware of the fact that the experiment itself requires students to be confident to some extent, and that a lack of confidence can thus have a significant impact on what is ultimately learned from the experiment:

> *If you're not confident enough to really try things, and you're waiting for somebody to tell you what to do, which can sometimes happen, just to be pushed through the experiment by the demonstrator is probably not the best way to go with it. (Developer 4, developer focus group)*

Those aims related to spectroscopy were not very clearly defined in the discussion with developers, but two broader themes were still identified: 'the principles of spectroscopy' and 'functionality of a spectrometer'. The 'principles of spectroscopy' includes the phenomena and principles that students were desired to become familiar with by means of the experiment. For example, one of the developers considered seeing Beer-Lambert Law by eye as one of the key learning objectives:

> *In lectures, students learn about Beer-Lambert Law, and they see spectra, but never do they see what is the Beer-Lambert Law. -- What's great about the spectrometer is, you can see it by eye, the absorbance, which is one of these wonderful things. For me, that's a great learning opportunity, because students tend to learn by doing, rather than sitting in a lecture. (Developer 3, developer focus group)*

In addition to Beer-Lambert Law itself, the students were also supposed to learn some general principles of absorption spectroscopy. As one of the developers explained, radiation absorbed by a sample is often talked about, which can create a misconception for a student that absorption spectroscopy is about measuring the intensity of light that is *absorbed*. This is not the case, however, and the experiment was intended to illustrate this to students:

> *What you're seeing is not what's been absorbed; it's what's not been absorbed. You only ever see the change in the stuff that gets bounced back. That's a really important concept, I think, for the first year. (Developer 2, developer focus group)*

The theme ‘functionality of a spectrometer’ consisted of issues which dealt with how the spectrometer works as an instrumentation. The learning objective that was stated in the laboratory manual, *to understand how a spectrometer works*, was not one of the learning objectives that the developers mentioned when asked. However, in other parts of the discussion it was made clear that developers felt it is still important for students to understand how a spectrometer works:

> *So I think it’s very important that people understand how a spectrometer works, because if you know what’s happening inside it, you can understand when it tells lies, when it doesn’t quite work, when it’s producing artefacts. (Developer 2, developer focus group)*

Furthermore, it was explained that one of the primary reasons for developing the experiment was that the first-year laboratory course did not include any experiments about the instrument itself before. Thus, the conclusion can be made that one of the learning objectives had to be, to some extent, to make students understand how a spectrometer works. However, none of the developers defined this to mean a component level understanding; this is, what are the roles of specific components in producing a spectrum and how do the components work together.

In addition to the aforementioned themes, developers also highlighted such themes as ‘learning by doing’ and ‘revision’ in the learning objective discussion. However, these were not classified as learning objectives as they rather describe the learning process than the aims or outcomes. Instead, in other phases of the discussion, developers emphasised the data processing to some extent. Both MATLAB and Excel were considered as particularly important programmes for students’ future studies, and therefore, learning how to use them was decided to be part of the experiment since the early stages of the designing process. The use of these programmes was also mentioned in the list of key outcomes, so it is justifiable to say that learning to use MATLAB and Excel for data processing was one of the learning objectives. The learning objectives stated in the laboratory manual and formulated based on developers’ discussion are presented in Table 2.

Table 2. Learning objectives of the experiment defined by the developers (adapted from the laboratory manual and developers' discussion in the focus group).

Learning objectives defined by the developers	
Laboratory manual	Focus group discussion
• To understand how a spectrometer works	• To learn 'research skills' (independent working, troubleshooting, decision-making, problem solving) • To gain confidence in the laboratory • To learn about the principles of absorbance spectroscopy • To understand how a spectrometer works • To learn using MATLAB and Excel for data processing

Despite all the aforementioned purposes and learning objectives that developers considered important for students to achieve, one of the developers admitted that they might have been a bit too ambitious with the experiment in the end. After revising all the stages of the experiment, Developer 3 draw a conclusion:

> *I think that was probably asking a little too much [the procedure as a whole]. Having them play is probably the way to go. (Developer 3, developer focus group)*

5.1.3 Demonstrators' and students' perspective on learning objectives

Demonstrators and students were also asked to state what they thought the learning objectives of the experiment were. In both the demonstrators' and students' responses, the recurring theme was the 'functionality of a spectrometer', although they thought this specifically as a component-level understanding. One of the demonstrators reasoned the learning objectives as follows:

> *I guess just knowing what's inside a spectrometer, because they use them throughout and so that they could, sort of, say what elements are*

in there, roughly in what order. (Demonstrator 1, demonstrator focus group)

The other demonstrator also emphasised the understanding of how the instrumentation works and explained why this is regarded as an important concept in the Department of Chemistry:

A lot of staff had issues with the fact that a chemistry student will go through the whole degree just bunging in a sample in the instrument, pressing play and having no idea how it works. So, really, it was just to allow them to understand equipment a bit better. (Demonstrator 2, demonstrator focus group)

The students' views of learning objectives were very similar to those of the demonstrators. Not all students expressed their opinion, but no one disagreed when Student 1 proposed that the purpose of the experiment was to *understand how a spectrometer works, and maybe to help to understand spectroscopy a bit more*. It was not completely clear what 'the understanding of spectroscopy' meant in practice to the student, but the functionality of a spectrometer was explained as follows:

Yes, so just how each part works together to give the spectrum, and then how you can use the data from it for other applications. (Student 1, student focus group)

Students were also asked whether they feel like they learnt something new about how a spectrometer works as a result of this experiment. A student expressed that they must have learnt something as they spent three hours doing it, but a few students wished they would have learnt more. For most of them, the experiment worked more as a revision and visualisation of what they had learnt before at the lectures.

For me, it gave me something to visualise, so us actually constructing it, and something, when I was revising it, that I would think, 'Yes, we did that.' But I don't think it helped my understanding as much as I would hope that it would. (Student 3, student focus group)

When the learning objectives defined by the developers (Table 2) were introduced to both the demonstrators and students, it turned out that neither focus group felt that these aims were fully met. First, it was found out that the learning objectives about the Beer-Lambert Law and the principles of absorbance measurements were not achieved at all as the demonstrators had, due to a lack of time, to cut off the actual absorption measurements out of the procedure. Thus, the final step of the experiment for the students was the plotting of the calibrated spectrum of white LED light. Furthermore, students felt that covering Beer-Lambert Law as a part of this experiment was not completely necessary in the first place, as one of the students stated:

> *Even if we hadn't seen an actual hands-on example, I feel like just from the spectroscopy lectures, we could still grasp what the Beer-Lambert Law was and what it means. (Student 1, student focus group)*

Another student agreed about omitting the Beer-Lambert Law and told that students had just carried out another experiment that focused specifically on absorbance measurements. Demonstrators had the similar kind of thoughts and they suggested that, in this context, the focus should be primarily on the instrumentation:

> *They have another Beer-Lambert Law experiment. The focus of this one should just be in learning about instrumentation. I think that's the strength of this experiment. (Demonstrator 2, demonstrator focus group)*

However, the demonstrators agreed with the developers that learning research skills, such as troubleshooting and problem-solving, was a large aspect of the experiment. Students commented on troubleshooting and problem solving in relation to the data processing but did not comment on this in relation to the building of the instrument and collecting of the data. On the other hand, data processing, in particular, was also a central part of the experiment according to the developers. Demonstrator 1 commented on the data processing being *hard but necessary* for students, even though it is not clear whether the demonstrator meant that the data processing is necessary to learn through this experiment or in general. According to one of the students, however, the data processing should rather be learnt somewhere else than in a laboratory:

> *--All the maths on the computer and comparing graphs – that is useful. But that's also stuff we can learn in our lectures and by reading. (Student 4, student focus group)*

Demonstrators considered teaching independent working to be an obvious part of the experiment, because, as Demonstrator 1 put it, *they just got a big box of 'stuff' and it is not told exactly what to do*. On the other hand, the demonstrators' comments revealed that the students needed a large amount of help, so, despite their goals, the degree of independence may not have reached the exact level that the developers originally expected. The students themselves felt that too much was expected in terms of independence, as the following student's comment exposes:

> *Yes, it's good to make us work independently, but I feel that there's only so much we can actually figure out on our own. I felt like there were several times where we tried to do it, and we just got stuck. Then we were still expected to figure it out on our own, even if we had got to the point -- where we'd started to give up, because we just didn't know what else to do. (Student 1, student focus group)*

Demonstrators' and students' opinions differed the most from each other when it comes to the question of gaining confidence. Although one of the demonstrators thought that some of the students might have lost confidence as a result of how they succeeded in the experiment, they eventually came to the conclusion that there were more signs of increase than decrease in students' confidence.

> *I think most of them gained confidence because, at the start, they were even too scared to put two things together, but, at the end, they were fiddling with something. (Demonstrator 1, demonstrator focus group)*

The students, however, felt that many of them did lose more confidence in the laboratory than what they gained, but they also admitted that they are able see why the experiment could have increased their confidence. The laboratory session was generally regarded as stressful and frustrating, because students *just kept doing the same thing and getting nothing reasonable (Student 3, student focus group)*. This is how a student described their general feelings about the laboratory sessions as a whole:

> *At the start, for the first hour, everyone was just like, 'It's a normal lab session.' But by the end, it just seemed that people were just giving up at that point. (Student 4, student focus group)*

Demonstrators' and students' opinions on learning objectives defined by developers are presented in Table 3. As these findings reveal, the only learning objective that both demonstrators and students agreed with was *to understand how a spectrometer works*. However, this learning objective was one of the least discussed by the developers, which indicates that developers did not consider it as the most important one. Furthermore, as this learning objective was the only one stated in the laboratory manual, it is not surprising that demonstrators and students considered it as the main learning objective. Therefore, it is not clear whether the demonstrators and the students actually felt that understanding of how a spectrometer works was something that could be learnt through this experiment or if they mentioned it just because it was stated in the laboratory manual. As for the rest of the learning objectives, students did not fully agree with any other objective, while demonstrators agreed, to some extent, with the learning objectives about research skills and gaining confidence. It is important to emphasise, however, that these findings do not necessarily prove whether the learning objectives were achieved or not, except those related to Beer-Lambert Law and absorbance measurements, which were not covered in this experiment due to a lack of time.

Table 3. Summary of the demonstrators' and the students' opinions on the learning objectives defined by the developers.

Learning objective	Demonstrators' opinions	Students' opinions
To learn 'research skills' (independent working, troubleshooting, decision-making, problem solving)	Large aspect of the experiment The degree of independence lower than usual	Troubleshooting and problem-solving not considered as a part of building the instrument Too much independence was expected
To gain confidence in the laboratory	More signs of increase than decrease in students' confidence	Many of them lost confidence
To learn about the principles of absorbance spectroscopy	Not covered Unnecessary part of the experiment	Not covered Unnecessary part of the experiment
To understand how a spectrometer works	Main learning objective Component-level understanding	Main learning objective Component-level understanding
To learn using MATLAB and Excel for data processing	Hard but necessary for students (unsure whether meant in this context or generally)	Unnecessary in this context

5.1.4 Demonstrators' and students' issues with the current experiment

Several issues with current implementation of the experiment emerged from the demonstrator and student focus groups. The discussion with the demonstrators revealed that the structure of the experiment was changed for this academic year. However, this did not emerge from the developer focus group, which is surprising. Demonstrator 1 described the change as follows:

> *So, after that [students struggling with the experiment], I completely restructured the experiment, so that was (the course leader's) advice. So, the first 15 minutes I spent doing a short course on optics. -- Then, after that, I told them to basically to ignore the lab manual because the whole point was that they just need to build spectrometer based on that. (Demonstrator 1, demonstrator focus group)*

This change was thus made in the beginning of the first laboratory session, but no changes were made to the laboratory manual, which students still possessed. Furthermore, Demonstrator 1 explained that the data processing part was restructured too: the original MATLAB script was replaced with a similar kind of programme containing an interface, which included its own instructions. The students were told about this as a part of the briefing in the beginning of the session, but only verbally. Not all the students, however, seem to have been aware of these changes and thus they kept on following the instructions of the laboratory manual, according to Demonstrator 1. Even though giving only verbal instructions to students was not explicitly stated as an issue by either demonstrators or students, verbal instructions were not completely understood by students, which can be considered as an issue.

Both the demonstrators and students expressed that the way instructions were written in the laboratory manual was one of the biggest disadvantages of the whole experiment. Both focus groups argued that the laboratory manual was *too wordy and vague*, which made it difficult for students to follow it in places. According to the demonstrators, students did not complain much about the spectrometer constructing part of the instructions, neither written nor verbal, but when students reached the data processing phase, the complaining about the instructions was described to be *non-stop*. Demonstrator 2, whose students used the written data processing instructions of the laboratory manual, described students' problems with the data processing as follows:

> *A big weakness, the data processing. They do find the steps particularly a bit hard to follow and I think, in some cases, they get bogged down with the spreadsheet to the point that they're, kind of, forgetting why they're doing… they're just copying and pasting formulas, they're not really sure why. (Demonstrator 2, demonstrator focus group)*

Even though the data processing was intended to be carried out differently in the group of Demonstrator 1, the results seem to have been as poor as with the other group. According to the demonstrators, only a few students understood what the data processing was about, regardless of which MATLAB script they used. As Demonstrator 2 explained, students were not familiar with the software which made using it, in this context, too challenging for them.

The data processing was not, however, the only problem with the laboratory manual. Both the demonstrators and the students called for the addition of visual guidance to the instructions, which, in practice, meant pictures and diagrams. As a prelab exercise, students were asked to draw a diagram of a spectrometer, which they would then use as a model for building the Lego spectrometer. The problem here, however, was that the spectrometer diagrams students found online were much more complex than what they were supposed to build.

> *So, they'll have a diagram which has 30 different components and they only get the most basic ones. So, I think it should be given to them and then they should explain it. (Demonstrator 1, demonstrator focus group)*

Also, the students recommended that such a diagram should be included in the laboratory manual. What is more, a spectrum of a white LED and a picture of an achievable spectrum produced with a Lego spectrometer were needed as a reference. A picture of an achievable spectrum was needed so that students would have known at what point their spectrum was good enough for moving to the next stage of the procedure, *instead of then spending most of the time trying to get to that point (when the spectrum is perfect)*, as Student 1 expressed.

In addition to the laboratory manual, both demonstrators and students expressed that the key deficiency of the experiment was that the 'real' aims of the experiment were not stated in the laboratory manual. According to Demonstrator 1, the goals should be made clearer to the students, because*, at the end, they were quite worried about being assessed*. In other words, as students did not know exactly what the expectations for them were, they were not sure if they had reached the goals which made them worried. Presumably, the lack of knowledge about the learning objectives did affect demonstrators' performance as well, but this did not emerge from their discussion. From the students' perspective, uncertainty about the learning objectives did affect them. First, it was clear that the students did not consider the building of the spectrometer as a main point of the experiment, though it was, to some extent, the core of it for the developers. For the students, the construction phase was just as a necessary step that would allow the measurements to be done. Thus, they found the time-consuming construction phase frustrating, or even distressing, because it prevented them from reaching their goal, which was to complete the whole experiment. One of the students admitted that it would have been beneficial to know that the learning process was the main point, but the number of pages in the laboratory manual would still have put pressure on them:

> *I think the concept of that would be reassuring [knowing it was all about the process] but when you've still got two or three pages of instructions, and you don't feel like you're going to get to that, even if they've said to you, 'It's not about actually doing that bit,' it still feels like you're kind of failing at it, because there's the potential to do that. (Student 3, student focus group)*

The great number of pages derives from the great amount of content of the experiment which was one of the reasons for the students' displeasure. As Student 4 stated, *it did not seem like it was even possible to do all of it in one lab session*. Thus, a 'lack of time' was a recurring theme in student focus group discussion. On the other hand, some students stated that the experiment was *long-winded* and that *it was not an efficient use of time*. Here, at least not all of them felt they had been constrained by time pressure. To make it more efficient, a student expressed that there should be a clear focus on either building the instrumentation or on the data processing:

> *I think it has to be either focused on Beer-Lambert Law and getting the data, and then just what you do with the data and all the stuff on the computer. Then make it easier to build it, so then, somehow, I would know how you would do that. -- Or make it about building the spectrometer, and then not really that much about the data; just about building the best one you can. (Student 4, student focus group)*

The issues that both demonstrators and students had with the current implementation of the experiment are summarized in Figure 4.

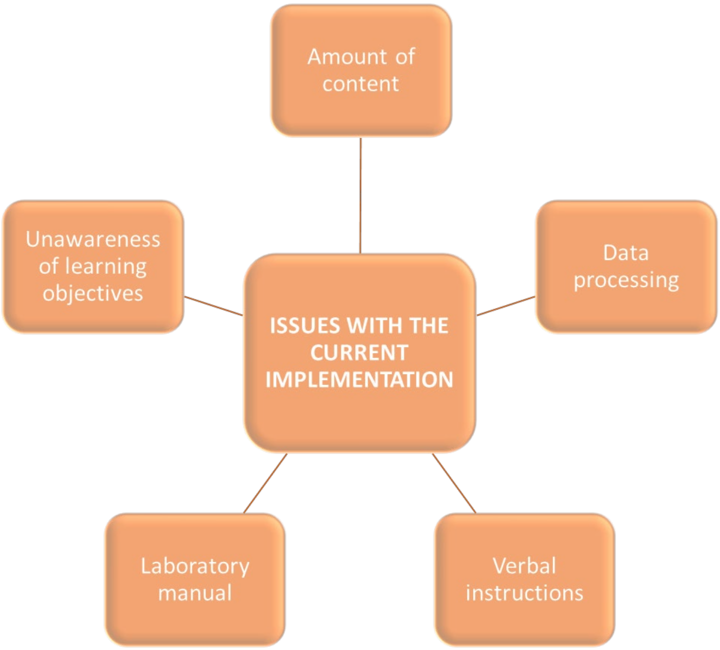

Figure 4. Summary of the issues with the current implementation of the experiment emerged from demonstrator and student focus groups.

5.1.5 Overview

As the number of learning objectives of the experiment indicate, developers were very ambitious with the experiment. Among other things, they wanted the experiment to teach problem-solving, to give students confidence in the laboratory, to help students to understand principles of absorption spectroscopy, and to learn how to process data. However, according to demonstrators and students, only a few objectives were achieved. Demonstrators and students believed that the experiment was aimed primarily at teaching how the components of a spectrometer work. Thus, the difference in perceptions about the aims of the experiment between the developers and the other two focus groups was remarkable. This may be attributed to the fact that the learning objectives were not well defined in the student laboratory manual.[1] First, the only defined learning objective, *to understand how a spectrometer works*, leaves too much room for interpretation. This is because *to understand* is an ambiguous, non-measurable verb.[12] Thus, *to understand* does not belong to the measurable action verbs defined by Bloom, which are recommended to be used for creating effective learning objectives.[14] Example of an action verb is, for example, *to identify* or *to express*. One of the tasks of learning objectives is to break down the activity that students are desired to carry out, which makes it easier for students to become aware of the expectations directed at them.[4] Instead, rather than breaking the task down into smaller 'units', the learning objective used here brings together potentially a great amount of smaller goals of which the *understanding* consists of. However, it was not clear, even after the focus group, what *to understand how a spectrometer works* explicitly means to the developers, and what the narrower learning objectives should be that indicate the understanding. These could include, for example, such aspects *as knowing what components constitute an instrument, how the characteristics of the components influence the instrument's performance and the performance assets and limitations of the instrument*.[36]

Second, one of the purposes of learning objectives is to communicate the teacher's aspirations to the students.[3] A requirement for the successful communication through learning objectives is to clearly state the learning objectives and make them visible to students.[4,5] However, most of the learning objectives that the developers presented in the focus groups, which I consider to be the 'actual' learning objectives, were not stated in the laboratory manual. As students and demonstrators were unaware of some of the learning objectives, the communication between them and the developers was deficient and affected the performance of both the demonstrators and students. This was something that both the demonstrators and students considered as a problem as well. It has also been stated that the planning of a teaching action should begin with clearly defining the learning objectives, which presumably was not the case with this experiment.[3] This conclusion was drawn because the developers did not present the learning objectives in the discussion in an exact, well-defined form, but rather expressed their own personal opinions on learning objectives. This indicates that the developers did not make the decision about the exact learning objectives together, in the beginning of the designing process. Furthermore, because the developers defined the desired characteristics of the experiment (Figure 2) more clearly than the learning objectives, a question arises whether they had chosen the means before the objectives.

Based on the demonstrators' and students' opinions, it can be stated that the implementation of the experiment did not completely align with all the learning objectives. It helped the students to revise how the components of a spectrometer work together, which is related to understanding how a spectrometer works. The demonstrators felt that students also learnt problem-solving, troubleshooting and decision-making, and gained more confidence to work in a laboratory. The rest of the learning objectives were not achieved. The vagueness of the laboratory manual, including the issues with the learning objectives, was clearly a reason for not achieving all the learning objectives.

Also, there seem to have been too much content and thus too many aims set for students' learning given the duration of the laboratory session. In comparison to the two previous open box spectrometer experiments that were described in the literature review and were reported being successful in teaching the chosen learning objectives, a few differences to this experiment can be identified.[34,38] In smartphone spectrometer experiment designed by Scheeline and Kelley, students were reported to have achieved the learning objectives in 45 minutes, but the learning objectives were narrower and related to a component-level knowledge.[34] Bougot-Robin et al. defined wider and more cognitively challenging learning objectives for the DIY spectrometer experiment, including understanding of the working principles of a spectrometer, data processing, decision-making and problem-solving.[38] These learning objectives were met by students, but they were set for a whole eight weeks' project. Thus, these examples prove that both narrower and wider learning objectives can be met using an open box spectrometer, but they need to align with the duration of the session.

5.2 How does the 'open box' nature of the experiment aid students in understanding how a spectrometer works?

5.2.1 Focus groups' thoughts on the open box structure

As mentioned before, the original idea of developing an open box spectrometer experiment evolved from the developers' observation that in general students do not know generally what is inside a spectrometer. However, the developers did not consider open box spectrometer only as an opportunity to literally see inside an instrument, but rather as an effective tool for learning. In their discussion, the central theme related to the open box nature was 'understanding the data'. Developers considered black box instruments producing the desired data for the users as a common problem, which leads to a situation where they do not necessarily know how the data is produced in practice. When internal processes of instruments are not understood completely, one simply relies on the data produced by a machine, which, according to the developers, is not always correct. Thus, the open box spectrometer was not only supposed to make the students understand how this specific spectrometer works, but also, more generally, to teach a critical way of analysing the data:

> *If you understand what you're doing, when something goes wrong, you know why it went wrong. An instrument will give you an answer. Is it the right answer? That's always the question, and more often than not,*

it's not. Understanding why it's not and what could have gone wrong, you need to understand what's actually inside the black box. (Developer 3, developer focus group)

The lack of critical thinking towards machine-generated data among students was said to be noticed in other contexts as well. Developer 1 stated that students tend to trust in what they see on a digital display *over any instincts that they have*. The developer explained that a consequence of this is, for example, that some students do not question even the most senseless results their calculators give them in exams, although those are often a result of their own errors in using the calculator. Thus, developers hoped that experiments like this would help students to think in a different way.

So, I think, for me, that [not questioning what's on a digital display screen] is one of the dangers of using black-box spectrometers, and one of the things that, hopefully, these kinds of experiments can help to dispel. (Developer 1, developer focus group)

For some of the developers, it seemed to be precisely the visibility of the open box spectrometer that they believed to support students' learning. The do-it-yourself nature combined with seeing the phenomenon, the Beer-Lambert Law, in practice was thought to lead to deeper understanding rather than just superficial memorizing. The demonstrators, however, did not comment much on the visibility of the experiment, but they admitted that this experiment is a unique learning opportunity for students, precisely because they cannot usually see inside an instrumentation.

Students, instead, wanted the experiment to be even more visual. They compared the Lego spectrometer to a simpler spectrometer they had used in other context to visualise how different kind of lights disperse into different kind of spectra. That spectrometer was just a cardboard box utilizing a CD as a diffraction grating. That experiment did not include collecting any quantitative data and was only used as a demonstration during the students' exam week. For the sake of simplicity, students judged the spectrometer to have worked well, and the clarity of the experiment helped them to understand what was to be understood. One of the students claimed to have learnt even more about spectroscopy by using the CD spectrometer than the Lego spectrometer. The student described the main difference between the spectrometers as follows:

Because you can hold it, and you don't have to worry about moving it or not moving it [the CD spectrometer]. You can adjust while you're *looking. Whereas with this experiment we did, you would adjust, then close the box and really carefully try not to move anything, and look, and then repeat. (Student 4, student focus group)*

In other words, the Lego spectrometer could not be viewed and adjusted while it was operated since, at that point in time, the box in which it was placed in had to be closed. For this reason, the visibility of the spectrometer was, in a sense, always lost when it was in progress. Thus, although the developers considered the visibility to be important for the learning process students underwent in this experiment, it was only present at times.

Perhaps more remarkable for students' learning than the open box nature itself was how the open box structure was put into practice. Namely, the students argued very strongly that the spectrometer was *too fiddly* and *awkward to work*, which seemed to have taken most of their attention related to the structure of the instrument. Indeed, some students supposed that the experiment would not have been too difficult otherwise, but the poor usability of the spectrometer made everything more challenging. Developers were also aware of the problems with the spectrometer, as a developer's argument indicates:

But I think the weakness is that once they've set it up, they knock it and get it wrong again. They spend a lot of time working on it and get it nice, and then you bump it once and it's all gone. (Developer 3, developer focus group)

Therefore, it took a long time to assemble the spectrometer, but it was still not possible to obtain it stable enough to not to be disturbed by even a minor hit. In addition, the students seemed to not have fully trusted the instrument they had built of Lego bricks themselves, which may have affected their performance. Although the developers considered the Lego spectrometer to be a *real, proper spectrometer*, one of the students did not think it was possible to achieve proper results with it:

It was quite annoying to try to get the spectrum right, because you can never get it exactly. (Student 2, student focus group)

5.2.2 Overview

The way developers thought that the open box spectrometer would aid students' understanding on how a spectrometer works was not completely clear. They believed that by simply seeing what is inside a spectrometer, students would gain a deeper understanding of some concepts related to spectroscopy, rather than, for example, by only using a black box spectrometer. The idea that illustrating the phenomenon in practice would make it better understood is logical and also widely accepted in chemical education.[56] This refers to *Johnstone's triangle* which determines the three basic components of chemistry: *macroscopic (observable phenomena), submicroscopic (molecular and atomic level) and symbolic domain (formulas and equations).*[56,57] By connecting these three domains, chemistry is believed to be understood better.[58] Illustrating the phenomenon is related to the macroscopic domain but the problem was that there was no detailed definition of what concepts were intended to be illustrated. The developers did not explicitly state that the primary purpose of the open box spectrometer was to increase students' understanding on how *the instrument* works. Rather, the instrument was considered as a tool to illustrate light absorption and the Beer-Lambert Law. Thus, the developers focused more on the phenomena than the instrument itself. Whether the open box structure would increase students' understanding of light absorption and the Beer-Lambert Law was not determined because the students did not have time to carry out absorption measurements, as explained in chapter 5.1.3

The developers' idea that the visibility of the inside of the spectrometer would help students' understanding did receive some support from the students. As presented in chapter 5.1.3, some students felt that the experiment worked well as a revision and visualisation of things they had learnt about absorbance spectrometers before. Still, some students did not feel that the Lego spectrometer was as visual as the CD spectrometer, which they felt had helped their understanding because of the visuality of the instrument. On the other hand, the students also emphasised the simplicity of a CD spectrometer, and thus one cannot be entirely sure which feature they had ultimately found more useful. In the case of the CD spectrometer, it was also not entirely clear what made it particularly visual in practice, which makes the comparison of that property between the two spectrometers difficult. The lack of visibility of the Lego spectrometer was identified by the fact that the 'open box' had to be closed whenever the spectrum was to be produced, and the consequence of this was that students could not see inside the instrumentation at the most critical moment: when the spectrum was visible. The same kind of 'shoebox' solution to prevent undesired light from causing background signal has been introduced in some previous studies but the temporary lack of visibility it causes has not been considered as a problem.[33,40] Even though using an open box spectrometer in a darkened room without covering the spectrometer has been suggested in a few previous studies, it has not been discussed whether this might affect the learning outcomes gained through open box spectrometers.[34,35]

Not much can be concluded about the direct impact of the open box nature on students' learning but one consequence of the open box structure was evident: the way the open box structure was set up had a negative effect on students' attitudes towards the experiment. When students found the completion of the construction of the instrumentation too challenging and meticulous, they got frustrated. This reduced their motivation, which in turn has a direct connection to learning.[4] Therefore, the potential positive effects of the open box structure on students' learning were inevitably obscured by the negative effects of assembling the instrumentation. The difficulty students face when using an open box spectrometer is common. For example, Grasse et al. paid particular attention in their spectrometer designing process to the fact that the time-consuming adjustment of the instrument would not be required between each measurement, as is typical of spectrometers utilising cardboard boxes.[37] Their solution to the problem, 3D printable housing around the optical path, does improve the usability of the instrumentation but, at the same time, gives away the open box structure of the instrument in the proper sense of the phrase. Thus, when making decisions about the structure of the spectrometer, it is essential to be aware of what is intended to be taught: if one wants to focus on teaching about the components and overall structure of the spectrometer, it is sensible to strive for a structure which shows all the components at all times, as is the case with the spectrometer designed by Scheeline and Kelley.[34] Instead, if the measurements and the theory behind them is of interest, such as in the experiment designed by Grasse et al., it is beneficial to use a spectrometer that is as stable and user-friendly as possible.[37] When it comes to the Lego spectrometer investigated in this study, this prioritisation seems to not have been done properly: the structure was not open enough to teach the component-level knowledge, and the structure was not optimal for focusing on the measurements and data either.

5.3 How does the assessment of the experiment determine the level of students' understanding of how a spectrometer works?

5.3.1 Practical implementation of the assessment

When developers were asked about the assessment of the experiment, Developer 1 explained that the assessment is carried out in a formative way, as formative assessment was regarded more suitable than summative assessment for this kind of experiment. The summative assessment was not considered appropriate here, because Developer 1 felt that *that would restrict the students from being as free to make mistakes as we wanted them to be*. Demonstrators regarded this as a sensible solution too, especially when taking into account that the experiment is to be done in the beginning of first-year studies, when students are just getting used to the laboratory work at the university. Additionally, demonstrators claimed that getting assessed can sometimes hamper students' performance in the laboratory:

> *I just don't know because if they have anything that's assessed, they always worry about getting the right marks and I think it is more of understanding the fundamental basics and just having a play with the kit and trying to get something to work. (Demonstrator 1, demonstrator focus group)*

Demonstrators were the ones responsible for the practical implementation of the formative assessment of students. Developers had defined demonstrators' job in this experiment as *asking the right questions* and *guiding students when they go off track*. In both the focus groups of developers and demonstrators, it was made clear that these two themes, 'asking questions' and 'guiding', were considered as the most important tools of formative assessment in this context. In practice, the demonstrators implemented the formative assessment by monitoring students in the laboratory and occasionally asking questions to evaluate whether students understand what they are doing and, above all, why they are doing it. However, the evaluations were not recorded but the feedback was verbal and immediate, as Demonstrator 2 explained:

> *They would get informal feedback from me verbally. Like -- if they didn't understand something, I would explain, or if they got an answer correct first time, I'd say, 'Good job', but nothing written, nothing quantitative. (Demonstrator 2, demonstrator focus group)*

In addition to verbal questions and guidance, the demonstrators also had the 'extension questions' in the student laboratory manual, which could be used to probe students understanding. Not all of them, however, were applicable, as some of them were related to the last stages of the experiment that the students did not have time to complete. However, half of these questions concerned the features of the spectrometer and how the design of it could be improved, and these questions were utilized by the demonstrators. Demonstrators found it useful to think about the improvements for the design, because that way students would have to think deeper about the instrumentation and evaluate what they have built. One of the demonstrators also suggested how the 'improvements' theme could be generally used in evaluating students' learning in this case:

> *So, then, if you asked them, 'If you had unlimited money, you could buy anything you wanted, how would you make this better?' very few of them could actually say what you would need to do. By the end of it, people would say, 'get a better diffraction grating, make this out of aluminium, make it more sturdy', or something like that. (Demonstrator 1, demonstrator focus group)*

However, it remained unclear whether this was done in practice or intended as a suggestion. For some of the laboratory experiments in the first-year laboratory course, students are required to submit a formal laboratory report afterwards, which they receive feedback on, but, as the demonstrators explained, this was not the case with this experiment. Instead, the feedback that students received afterwards was in a form of video, which summarized the main content of the experiment. In general, the developers also mentioned that the practical skills of first year students are mainly assessed summatively in the end of the academic year as a part of their open-ended project.

5.3.2 How were demonstrators prepared for the assessment?

Both developers and demonstrators were asked about how the demonstrators were prepared for assessing students formatively in this experiment. Developers explained that each demonstrator is required to do the experiment herself or himself first. At that time, they also have an opportunity to ask questions about the experiment. Developer 1 stated that the demonstrators are usually told what questions they should ask students during the laboratory session, but in this case, there was an exception made and the demonstrators were left to *come up with the appropriate things to go through (Developer 1, developer focus group)*. When demonstrators were asked about how they were advised to assess students, their opinion was that no actual instructions on this were given to them:

> *We weren't formally told that we had to assess them because this one doesn't have a report. Yes. Really, it's just making sure they understand informally is my goal. (Demonstrator 2, demonstrator focus group)*

However, the demonstrators themselves stated that they explicitly evaluated students' understanding by asking questions and subtly guiding students in the right direction, which is a form of formative assessment. Thus, this may be just a matter of definition: the demonstrator might have thought that 'to assess' is synonymous with 'to assess summatively', which it is not. Regardless of that, it was clear that the demonstrators were not specifically told what the learning objectives of the experiment were, that is, what the formative assessment should primarily focus on. After the developer focus group, it was not clear either whether some guidelines about the assessment and its detailed purpose and implementation was determined. It was discovered that none of the developers present in the focus group were responsible for defining the guidelines for the assessment. However, it appeared that there was also a fifth person, who has since left the University, involved in the designing process, who was responsible for the demonstrator manual. This demonstrator manual may have included some advice for the demonstrators as well. Developer 4 explained the guidelines for demonstrators as follows:

> *--from what I've seen of it, I think it was like, if this much time has passed, and they haven't got past a certain point, to make sure that they get the full range of trying to get past every stage of the experiment. So it's a complete thing, it's maybe to drop some less subtle hints as to how it should be built. (Developer 4, developer focus group)*

5.3.3 Assessment from students' perspective

The assessment-related theme that emerged the most in the focus group of students was 'guidance', or more specifically, the level of guidance. It was found that students wanted much more detailed guidance per se. They said that the experiment was fun at first, but, as time went on and they could not get any further with it, they felt they should have got more hints on how to approach the problem.

> *Yes, I feel like when we were building it, sometimes, we were just told that it was wrong, but not necessarily why it was wrong. (Student 1, student focus group)*

However, they were clearly pleased with the nature of the feedback changing towards the end of the experiment:

> *Half-way through, the feedback kind of changed to being, 'Maybe think about this,' or, 'Think about that.' If that had been like that from the start, maybe, we would've progressed a bit quicker. Because I think a*

> *lot of people just didn't understand it well enough to know what changes to make. (Student 4, student focus group)*

On several occasions, students' statements reflected that because they did not know what they were doing, they felt that they *were just doing it for the sake of doing it (Student 1, student focus group)*. In addition, students regarded the briefing in the beginning of the experiment to have focused too much on unnecessary things, from their perspective, which did not help them with carrying out the experiment.

> *--there was a lot of emphasis on what the data was and things like that, but not really too much emphasis on how it all works and, when we're building it, things that we need to make sure we're doing, and things that we should try changing. (Student 1, student focus group)*

Students opinions on feedback, other than the feedback they received during the experiment, were also probed. Not all of the students had watched the video feedback they had received after the experiment, because they were too frustrated with the experiment. Since the post-lab report was not done in this case, the students did not receive any other feedback afterwards, but on the other hand, neither did the students feel that *there was a lot to actually give feedback on (Student 3, student focus group)*.

5.3.4 Overview

Assessment turned out to be a challenging topic in focus group discussions, as it was clearly not a topic that all the developers and demonstrators were completely familiar with. The overview of the assessment was that the premise of it was fair, but it was not designed to measure in detail the achievement of the learning objectives. The decision to carry out the assessment formatively can be considered justified, as most of the learning objectives presented were abstract and they would have been very challenging to measure in a form of laboratory report. Also, the task defined for demonstrators, guiding students toward the desired goals by *asking the right questions*, is a completely valid way to conduct formative assessment.[24] The problem here, however, was that the demonstrators' perception of the purpose of the experiment was not exactly the same as that of the developers. A prerequisite for effective formative assessment is that the teacher or supervisor has a clear sense of the goals of the task and that the guidance of the students is intentionally aimed at achieving these goals.[24,26] Obviously, this was not the case with the assessment of this experiment, as the objectives were not unambiguous and not fully known by the demonstrators. Based on my interpretation, it can be inferred that the indicators that demonstrators used for students' understanding on how a spectrometer works were the building of the spectrometer and whether they got it completed and whether they managed to give suggestions for how to improve the structure of the instrument. However, both these determine students' understanding very roughly. Also, the latter was not used systematically, as not all students had considered suggestions for improvement.

According to the developers, the demonstrators were not given any pre-considered questions to be used in carrying out the assessment, but no specific reason was given for this solution, which deviated from the normal practice of the course. It did not appear from the discussion of the demonstrators that they had prepared such questions for themselves in advance either. Thus, it can be concluded that the demonstrators used, to some extent, a so-called *on-the-fly* formative assessment, where the questions posed to the students were formed spontaneously, depending on students' actions.[22] However, despite its spontaneity, informal formative assessment is also meant to be learning-goal guided, so it is equally challenging to implement such an assessment without accurate knowledge of learning objectives.[24] Judging by the developers' statement about the guidelines for assessment, the demonstrators were not actually supposed to direct their guidance to the achievement of the learning objectives. The primary goal was to get students to complete the required steps of the procedure, and to provide more help towards the end of the experiment.

For students, formative assessment was conveyed in the form of verbal feedback. No comprehensive image of the overall quality of the feedback was formed, but based on the issues raised by the students, the feedback from the demonstrators was, at times, considered too vague, it did not always focus on the issues relevant to the experiment and thus did not help students to understand what the experiment was really about. It can be concluded that the verbal feedback did not completely align with the three descriptive questions of effective feedback defined by Hattie and Timperley.[27] One of the most important functions that feedback has in supporting learning is to clarify the objectives and success criteria for the learner, which is also what Hattie and Timperley refers to with the question *Where am I going?*.[21,27] It is obvious that too vague and irrelevant feedback does not meet this criterion, but, as has been mentioned several times before, the objectives and criteria for success were not entirely clear to either the demonstrators or the students. One of the specific purposes of the experiment, according to the developers, was to teach independent working and problem-solving skills to students. The demonstrators were not supposed to give students too detailed hints too early in the first place. This may have appeared to students as they were left on their own. The criteria for effective formative feedback presented by Shute also state that learners should not be given the right answers too early in order to let them to try to solve the problem on their own first.[28] However, the demonstrators may have deferred giving more specific hints for too long in this case. Instead of starting to give more specific hints halfway through the experiment, it would have been an option, for example, to give staggered, different levels of hints depending on how many times the students had tried to solve the problem themselves. To return to the questions defined by Hattie and Timperley, the students felt that the feedback they received in the end of the experiment was more in line with the question *Where to next?*, which means what activities should learners perform in order to reach a desired outcome. Instead, no evidence was provided for or against as to whether the feedback provided an answer to the question *How am I going?*; in other words, what is the learner's current level of understanding or competence.

6 Limitations

A possible limitation of this study is the small size of the focus groups. The number of participants of the demonstrator focus group could not have been increased because all the demonstrators of the experiment were already involved. It was acknowledged that the group size of two is not optimal for a focus group as no studies were found to suggest using group size smaller than three. As for the developer focus group, it turned out that there was also a fifth developer who participated in the designing process, and it could have been beneficial to get this developer involved in the focus group too, but they had left the University and so were unable to participate. However, the sample size can be considered more as an issue in the case of the students because, in this study, four students represented the perspective of all the first-year Chemistry students in Durham University. The decision to have only four students in a focus group was made because keeping the group size between focus groups as equal as possible was considered logical. Some previous studies also support the use of small group sizes.[44,50] The potential disadvantage of small sample size is that the opinions that the students share may not represent the opinions of the majority of students. To increase the representability, more focus groups of students could be used. Furthermore, those students who carried out the experiment the previous year could also have been included in the focus groups.

The way the focus groups were carried out bares some potential limitations with it as well. First, the focus groups were supposed to be semi-structured but they were finally much closer to structured than unstructured discussion. The questions prepared for focus groups were defined in detail to ensure that the concepts that the moderator considered important would be discussed. However, the discussions followed the predetermined structure quite strictly, which was not the purpose. Therefore, the involvement of the moderator in the focus groups was strong, which may have affected the themes that emerged from the discussions. Many themes were identified from the discussions, but the question arises whether some important themes did not emerge because of the pre-determined structure of the discussion. This limitation could be overcome by rephrasing the questions to broader themes which would be given to the participants to discuss. This would also decrease the 'interview-alike' set-up which was present in these focus groups, and the moderator could focus on observing the participants rather than interviewing.

Although the moderator may have been too involved in the focus groups when it comes to the structure of the discussion, more involvement may have been necessary when the participants stated their opinions. As the participants were not challenged to argue their opinions, a deeper understanding about their way of thinking was not always reached. To some extent, this made the interpretation of the results challenging. For example, one of the students did not consider problem-solving and troubleshooting as part of the building process of the spectrometer but treated those abilities as if they were to be learned through data processing. However, the reasoning for this remained unclear because the student was not asked to explain this any further. Thus, in order understand the rationale behind the opinions of each focus group, asking more 'why?' questions may have been useful.

7 Conclusions

7.1 Summary and key findings

This research aimed to evaluate the open box spectrometer experiment that was developed for a first-year undergraduate chemistry laboratory course in Durham University. By conducting the focus group discussions with the developers, demonstrators and students, and analysing the transcripts of the focus groups thematically, answers to the following research questions were sought:

1. *How does the current experiment align with the original learning objectives of the experiment?*

2. *How does the 'open box' nature of the experiment aid students in understanding how a spectrometer works?*

3. *How does the assessment of the experiment determine the level of students' understanding of how a spectrometer works?*

It was found that the demonstrators and students considered the idea of constructing an instrument using Lego bricks fun and unique, which can be utilized in revision purposes. However, findings from the focus groups suggest that the current experiment did not completely align with the original learning objectives. By means of the experiment, developers wanted the students to learn 'research skills', such as independent working and problem-solving, to gain confidence, to learn about the principles of absorbance spectroscopy and spectrometer as an instrument and learn data processing. However, the students felt they only learnt about the components of a spectrometer, while the demonstrators believed students to have also practiced problem-solving, troubleshooting and decision-making skills and gained confidence. Four potential reasons as to why the learning objectives were not achieved by the students were identified. First, most of the learning objectives were not stated in the laboratory manual, thus the demonstrators and students were unaware of the expectations of the developers. Second, the only learning objective that was stated in the laboratory manual, *to understand how a spectrometer works*, was not clear and measurable. Because of the ambiguity of the learning objective, students and demonstrators seem to have interpreted the learning objective in a different way compared to the developers. Third, the instructions that students received, especially the laboratory manual, were found to be too vague and did not provide enough support for students to complete the experiment. Fourth, there was too much content in the experiment compared to the duration of the laboratory session. Thus, the experiment could be improved by increasing the communication between developers, demonstrators and students and by reducing the content of the experiment.

The open box nature of the experiment was found to aid students, to some extent, in understanding how a spectrometer works by providing a context for the inner workings of a spectrometer. Thus, students considered the visibility of the inside of the instrument beneficial for connecting the different domains of chemistry.[57] Both students and demonstrators felt that this open box spectrometer aimed at teaching students about the components, particularly what the specific role of each component was and how they worked together. The developers, however, believed that the open box nature would aid students in understanding the light absorption, but this was not discovered because the absorption measurements were not accomplished. An indirect effect that the open box nature had on students' learning was the frustration which students experienced because of the difficulties in building the spectrometer. The building phase was time-consuming but did still not result in a stable, user-friendly instrument. Furthermore, it was suspected that closing the open box instrument with a cardboard box during measurements may have decreased the visual aspect of the instrument. Because students regarded the visibility of the components important for their learning, the decision to 'close the box' may have hindered their understanding.

The experiment was assessed formatively, and the demonstrators were in charge of the implementation of the formative assessment in the laboratory. The developers did not state guidelines for formative assessment in detail. This was left to the demonstrators. Because the demonstrators were not aware of the exact learning objectives, such as what the students should understand about the inner workings of a spectrometer, the implementation of the formative assessment could not be designed to determine the level of achievement of the learning objectives precisely. The formative assessment was carried out in an informal way by the demonstrators. Two gauges of the students' understanding of how a spectrometer works were evident from the demonstrator focus group: whether students managed to build the spectrometer and whether they were able to give suggestions for how to improve the design. The latter was not, however, used systematically with all the students. Finally, the formative feedback that students received did not meet all the criteria of the effective formative feedback. It did not clarify the objectives and the criteria of success to students. In order to improve the experiment in the future, it would be beneficial to design the means of formative assessment to align better with the learning objectives. In practice, this means that demonstrators should know the learning objectives. Furthermore, their guidance of students should aim at achieving those specific objectives.

7.2 Future work

While doing my research and reading the previous studies on open box spectrometer experiments, several gaps in the coverage of those studies were identified. Although the open box spectrometers are often considered superior to the black box spectrometers in teaching students the internal processes of a spectrometer and the physical phenomena related to them, no comparative studies between open box and black box spectrometers were found. As open box spectrometers are becoming more popular, there is a clear need for scientific evidence on whether using the open box spectrometers leads to better learning outcomes than using the black box spectrometers, and what these learning outcomes might be. Does an open box spectrometer provide students with better ability to identify limitations of the instrument than a black box spectrometer? Are students more capable of explaining how a spectrum is produced when they have seen it by eye? This kind of questions would be fascinating to explore. One could do this by setting up two experiments which are identical otherwise, but one would utilise an open box spectrometer, while the other one would be carried out using a black box spectrometer, and by comparing the learning outcomes in the end.

Another interesting research topic, which emerged from the student focus group as well, would be the potential impact that 'closing' the open box spectrometer has on students' learning. The majority of the open box spectrometers, including the one developed in Durham University, need to be closed in a box or housing in order to produce a spectrum, but some examples of using a completely open-structure spectrometers in a darkened room have been introduced. These two different approaches have not been studied in comparison to each other so far, but if the visibility of the inside of the spectrometer really aids students' understanding, reducing the visibility by closing the structure could potentially have an effect on the learning process. The fact that this topic emerged in a student focus group of this study supports this line of thought. It may be worth to explore whether students understand some spectroscopic concepts better when they can see and modify the inside of the spectrometer during the measurements as well.

8 Appendices

Raw data from focus groups, the ethical approval of the research and Excel file containing the thematic analysis filed electronically as Appendices.

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