Evaluating Students' Learning from Laboratory Investigations

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Abstract

The concept of investigation is a central concept in science. Throughout the centuries, both the meaning of the concept and the characteristics of the processes associated with a scientific investigation have been strongly dependent on the dominant views of science. Nowadays, scientific investigation should be conceptualized as a problem-solving activity. Within the context of Science Education, laboratory investigations have had no clear meaning and been often non-differentiated from other types of laboratory activities. Laboratory investigations should be conceptualized as problem solving activities enabling students to both develop different types of knowledge (conceptual, procedural and attitudinal knowledge) in an integrated way and get into contact with the methods of science. Hence, the evaluation of students' learning from laboratory investigations should concentrate on all these dimensions and be consistent with the holistic nature of this type of laboratory activity. Thus, the objective of this paper is to discuss the evaluation of students' learning from laboratory investigations focusing on both the issues that can be evaluated in the different phases of an investigation and how those issues can be evaluated.

Introduction

Nowadays, scientific inquiry should be conceptualized as problem solving (Gott & Dugan, 1995), aiming at answering to a specific question or finding a solution for a problem related to the natural world. For someone to have a problem, they first need to be perplex (Tobin, 1990). Then, they need to imagine and put into practice a strategy to solve a problem whose solution and methods of resolution are new to them. Hence, the concept of scientific investigation acknowledges a variety of possible sequences with interwoven steps and is no longer consistent with the idea of a fixed sequence of steps.

Although with different emphasis over diverse periods of time, teaching about scientific inquiry has for a long time been a goal of science education (Abd-el-Khalick et al., 2004). However, in the practice of science education the concept of investigation has often either stuck on *the* scientific method or been identified with other concepts within the scope of practical work and has not been properly differentiated from other types of laboratory activities. This conceptual confusion is at least in part responsible for the low use of real laboratory investigations as well as for the low importance given to them when students' evaluation is at stake.

Objectives

The objectives of this paper are: to clarify the meaning of investigation in science education contexts; to discuss the structure, requirements and types of knowledge involved in a laboratory investigation; to discuss the evaluation of students' learning from laboratory investigations.

The concept of investigation in science education

The idea of investigation as problem-solving activity (Woolnough & Alsop, 1985; Gott & Dugan, 1995; Leite, 2001) seems to deserve reasonable consensus. Thus, investigations are conceptualized as activities that require students to become actively involved in the resolution of a problem. Like in science, investigations may be carried out through several sorts of resources (Tobin, 1990; Leite, 2001), namely the teaching laboratory. However, investigations are different from laboratory work, as the latter has not necessarily to do with problem solving. Besides, hands on activities do not guarantee inquiry (Huber & Moore, 2001). Students may be manipulating lab equipment without understanding the purpose of what they are doing and they may rather be cognitively involved when watching a teacher's demonstration (Gunstone, 1991). However, as we have argued elsewhere (Leite, 2001), it would be nonsense to ask students to plan an activity in order to solve a problem and prevent them from carrying the laboratory procedure, unless their safety is at stake.

These ideas about investigations require a major shift from "student as technician" to student as "creative scientist" with sole responsibility for inquiry. This does not mean that a science course should be taught entirely through investigations. Besides, when we teach science we want students to learn the already constructed science rather than to construct new science. This means as that students would have the opportunity to feel what it is like doing science and that when teachers plan to use an investigation in their science courses they should allow students to command the process and act only as facilitators. To be able to do so, teachers need to become aware of the issues discussed above because, contrary to what they usually tend to do (Huber & Moore, 2001), they cannot rely on textbooks to teach students about the processes of science. This is due to the fact that some recent textbooks continue to convey the idea of *a* scientific method (McComas, 1998) and to confound fundamental concepts on this issue, instead of emphasising a wide variety of techniques, values, modes of reasoning, and dispositions that are believed to characterise scientific inquiry (Zachos et al., 2000).

Performing laboratory investigations: types of knowledge involved

Being problem-solving activities, investigations are open-ended, divergent activities and are therefore "unlikely to be appropriate for the 'discovery' of a certain, predetermined fact or theory" (Woolnough & Allsop, 1985, p. 43). In fact, investigations require students to select or re-interpret a problem, to acknowledge it as their own, to plan and put into practice a strategy to solve it, to evaluate results and to settle the solution. Students also need to be able to continuously evaluate their actions and decisions in order to revise them whenever necessary. Hence, Gott & Duggan (1995) emphasised the role of procedural understanding in the development of an investigation. Procedural understanding corresponds to "the thinking behind the doing" (Gott & Duggan, p. 26). Thus, it does not focus on the actions themselves but rather on the decisions that have to be made about what and how to do and relating it to objective evidence, which is a requirement of a laboratory problem solving process. Figure 1, based on the APU problem solving chain (quoted by Woolnough & Allsop, 1985), shows the main steps of a laboratory investigation and organises them into four main phases, as follows:

Phase 1 - It is a *pre-laboratory* phase that comprises and goes from the initial contact with the problem to the moment when everything is prepared to start the work with laboratory equipment;

Phase 2 - It is the *laboratory* phase and it comprises the implementation of the planed laboratory (experimental or not) procedure with the associated data collection;

Phase 3 - It is a *post-laboratory* phase that is concerned with data analysis and interpretation, evaluation of results and either elaboration of the conclusion or the reformulation of one or more steps of one or more of the three first phases;

Phase 4 - It is the *final post-laboratory* phase and it focuses on the *Communication/ publication* of the problem solving process and its results. It compares to the scientists' presentation of a conference or publication of a paper, and therefore has to do with the processes of science.

As shown by Figure 1, an investigation requires continuous reflection on design and implementation in the light of the problem as set and in the requirements of the data to answer it. Unfortunately, this characteristic of investigations is missing in most laboratory work carried out in schools (Watson & Wood-Robinson, 1998).

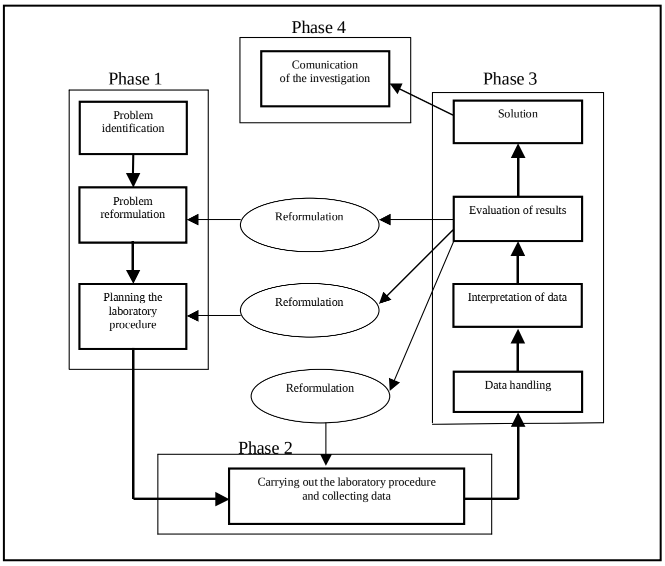

Figure 1: Phases of a laboratory investigation

In addition to conceptual and procedural knowledge, an investigation requires attitudinal knowledge that may also develop throughout all the phases of an investigation. Within the context of this paper, relevant attitudinal knowledge includes specially aspects that are related to the so-called scientific attitudes (Hodson, 1994), that is divergent reasoning, openness of mind, creativity, persistence, rigor, interpersonal co-operation, etc. Although with different emphasis, the diverse scientific attitudes are required and develop through all the phases of investigations.

The types of knowledge mentioned so far are explicit knowledge in the sense that people may be aware of them. However, there is some evidence that people may perform without being able to explain what they are doing and why they are doing it in such way. This means that they are using implicit knowledge, which may have been acquired unconsciously, by going through the processes, or consciously and then forgotten (Masters & Nott, 1998). Implicit knowledge is developed with practice, it is often not clearly articulated, and it is used along with explicit knowledge. In investigations much tacit knowledge is used when decisions are taken (Hodson, 1992). This does not mean that implicit knowledge is more important than explicit knowledge (Toh & Woolnough, 1993) but simply that success on an investigation is partly due to implicit knowledge that cannot be explicitly taught). Rather, it is developed when performing investigations.

Table 1 (columns 1 to 3) makes it explicit the types of knowledge required by the different phases of an investigation. The specific conceptual knowledge required by a certain investigation depends on the science content the investigation focuses on. This type of knowledge cannot therefore be specified in a general account like this one. It is mentioned in table 1 to emphasise that there are phases of the investigation process in which this type of knowledge is more necessary than it is in others.

As far as procedural knowledge is concerned, it is required over all the phases of an investigation, being different the procedural contents relevant in the various phases. Although the contents mentioned are based on De Pro (1998), some adaptations were made to account for the ideas discussed above. The order given to the contents does not correspond to the order by which they are used and the contents are not all necessarily used within the scope of a certain investigation. It is worth noticing that there are diverse types of investigations (Gott & Duggan, 1995) that require diverse types of procedural knowledge. In fact, variable-based investigations (involving control and manipulation of variables) have different procedural requirements from, for example, the measurement based investigations (focusing on how to measure a quantity that cannot be measured directly with available instrumentation).

Table 1: Evaluation techniques to be used in the different phases of a laboratory investigation

Investigation phase	Type knowledge	Contents	Evaluation technique
Phase 1 Pre-laboratory	Conceptual	Depending on the investigation	Test, interview and analysis of documents
	Procedural	Problem: identification and reformulation Prediction and/or Hypothesis formulation Variables: Identification and relationships Problem solving strategies: Identification, evaluation, selection of general strategies Laboratory procedure: lab techniques, measuring instruments, apparatus, steps Analysis of literature	Interview and analysis of documents
	Attitudinal	All main contents	Observation and analysis of documents
	Implicit	Cannot be specified	Cannot be observed
Phase 2 Laboratory	Procedural	Handling equipment, measuring instruments Implementation of lab techniques Observation Measurement	Observation
		Register of data	Analysis of documents
	Attitudinal	All main contents	Observation and analysis of documents
	Implicit	Cannot be specified	Cannot be observed
Phase 3 Post-laboratory	Conceptual	Depending on the investigation	Test and analysis of documents
	Procedural	Data: analysis and transformation Error analysis Classification and ordering Interpretation of results Modelling: use and construction Evaluation of results Identification of necessary reformulation Elaboration of conclusions Identification of the solution Analysis of literature	Analysis of documents, interviews
	Attitudinal	All main contents	Observation and analysis of documents
	Implicit	Cannot be specified	Cannot be observed
Phase 4 Communication	Conceptual	Depending on the investigation	Test, interview and analysis of documents
	Procedural	Analysis of literature Organisation of the report Publication of the report	Analysis of documents and interviews
		Presentation	Observation and interview
	Attitudinal	All main contents	Observation and analysis of documents
	Implicit	Cannot be specified	Cannot be observed

Attitudinal knowledge is not specified in table 1 because the diverse types of attitudinal knowledge are needed in the different phases of an investigation and, as will be discussed later, have similar requirements in terms of evaluation.

The nature of implicit knowledge prevents us from knowing it well and therefore from specifying its components too. Anyway, implicit knowledge to be used in each phase of the investigation is closely related to the actions and decisions that students must take.

In summary, all phases of an investigation require attitudinal knowledge and implicit knowledge, all but the second phase require conceptual knowledge and all phases require procedural knowledge. As far as evaluation is concerned, the main challenge is to find ways to evaluate the diversity of explicit knowledge acquired or developed by the students without missing the global nature of the task.

Evaluating students' learning from laboratory investigations

Evaluation can be undertaken in diverse stages of the teaching and learning processes, carried out in several different ways and by different agents. The when and how to evaluate and who evaluates depend on the purpose of the evaluation. The same applies to the evaluation of students' learning from laboratory investigations.

Evaluation: Purposes, techniques and periodicity

To some authors (Geli de Ciurana, 1995; Gott & Duggan, 1995) the traditional functions of evaluations (diagnostic, formative and summative functions) also apply to the evaluation of students' learning from laboratory activities. However, Hodson (1992) adds two other functions: the evaluative and the educational functions. He argues for evaluation and assessment to become part of learning. Hodson believes that evaluation should provide teachers with information about the effectiveness of the curriculum experiences, in order to assist curriculum decision making and planning (evaluative function), and enhance and promote learning by engaging students in interesting and significant experiences aimed at developing further insights and understanding (educational evaluation). The over exaggerated concentration on summative evaluation withdraws attention from the others (Hodson, 1992; Black, 1998). A correct evaluation of students' learning from laboratory activities requires both proper attention to be paid to the functions mentioned by Hodson (1992) and evaluation be consistent with the context of implementation of laboratory activities (Gott & Duggan, 1995).

In the case of investigations this is especially important, as students cannot be "abandoned" to themselves during the course and wait for feedback until the end of it, when the results of assessment are provided. If they are to learn how to investigate they need to get feedback from their attempts to investigate as often as possible, in order to become aware of their difficulties and to improve their performance. This need requires formative evaluation to be carried out whenever investigations are undertaken or at least as often as possible. It should be noticed that although summative assessment is concerned with achievement (Fairbrother, 1989), it can also provide useful feedback (Swain, 2000) to students and teachers. The point is that it would not make too much sense without the use of formative evaluation; one would be assessing students without doing everything that one should to help them to learn.

Based on several authors (Alberts, Beuzekom & Roo, 1986; Doran, 1978; Tamir, 1990; Giddings, Hofstein & Lunetta, 1991; Hodson, 1992; Gott & Dugan, 1995), Leite (2000) synthesised the different types of instruments that can be used to evaluate students' learning in the laboratory and related them to the data collection techniques mentioned by DeKetele & Roegiers (1996). Table 2 (translated and adapted from Leite, 2000) shows this synthesis and relationships. Different techniques concentrate on diverse dimensions of students' knowledge and competence. Thus, an adequate combination of techniques and instruments is needed for a comprehensive evaluation of students' learning. As an investigation is more than the sum of the parts, an adequate evaluation of students' ability to perform investigations requires attention to concentrate on the synthesis of procedural understanding (Gott & Duggan, 1995), rather than on individual concepts of evidence. The use of diverse evaluation techniques and instruments, either during the course or within the context of practical exams, and the collection of information from the diverse relevant elements is necessary but not sufficient to come to an overall judgement. The holistic nature of investigations requires that performances on the different elements and phases of the investigation are compared and interrelated, so that a global (even subjective) evaluation of the performance on the investigation is carried out. Lab reports make sense within the context of investigations as they require students to tell about what they have done, how and why (they compare to scientists' research papers) but for the reasons mentioned above they are not enough (they do not provide evidence about how well students performed in the lab).

Table 2: Techniques and instruments of evaluation

Number of Techniques	Types of Techniques	Instruments
Single technique	Inquiry	Written tests/exams Written questionnaires (opinion, attitude) Interviews guides
	Observation	Observation grids Checklists Field notes (Unstructured observation)
	Analysis of documents	Lab notebook Portfolio Lab report (traditional or Gowin' s V) Self-assessment sheets
Multiple techniques	Inquiry + Observation + Analysis of documents	Practical exams

Another point that is worth rising is that the evaluation of students' learning from laboratory activities can be continuous, periodical or both. Despite the fact that continuous evaluation has the advantage of giving immediate feedback to both teachers and students, research (Bennett & Kennedy, 2001) indicates that it is not a common feature of science teachers' practice. However, continuous evaluation is the one that best suits the purposes of formative evaluation and should be implemented whenever investigations are carried out. Due to their complex and holistic nature, a more global approach should be put into practice from time to time with summative purposes. The evaluation of students' learning can be carried out either by the members of the class - teacher and/or students- or by external examiners. Teachers' evaluation of their own students can be subjective, as it may be influenced by teachers' expectations. Fairbrother (1989) mentions two conflicts that occur with continuous teacher evaluation. The first is that the same information is used to provide feedback and also for the award of a final grade. The second is that teacher has to fill two different roles, that of helper and that of judge. These conflicts interfere with students' performance and reduce the reliability of the information collected. They can be reduced by explaining students the relative importance of both types of evaluation and of both teachers' roles but they will hardly be overcome. The use of external examiner may avoid the inconvenience of teachers' assessment and there is even some evidence (Bennett & Kennedy, 2001) that teachers as well as students may benefit from the presence of an external examiner. Nevertheless, it is hardly compatible with continuous evaluation and requires especial organisation in terms of tasks, schedule, etc. Giddings, Hofstein & Lunetta, (1991) point out that examination by external examiners may suffer from several drawbacks, namely different examiners may use different criteria, due to large numbers of examinees they may tend to rely on written material rather than on the observation of individual students, and the activities have to be chosen bearing in mind that they have to be completed in a reasonable time, instead of taking into account relevant science education criteria. Students can also participate in the evaluation process as self-evaluators. The main advantage of this is that students become aware of what they are able and of what they are unable to do (Gott & Duggan, 1995). Of course, students may be subjective in their judgements but if self-evaluation is used in conjunction with other techniques students' awareness of their limitations can even be improved. On the other hand, students produced self evaluation documents can also be taken as documents to be used by the teacher for students evaluation as they show how appropriately students evaluate their own learning an d how they progress in that job.

As far as investigations are concerned, it seems appropriate to have teachers continuously evaluating their students with formative purposes and to have students evaluating themselves, not only through self-evaluation but also through peer evaluation. Investigations are not mechanical individual enterprises. Involving students in the evaluation process may provide opportunities for them to understand it.

Evaluation of students' learning: Types of knowledge and techniques

Different types of laboratory activities have diverse conceptual, procedural and attitudinal demands and can promote the learning of different conceptual, procedural and/or attitudinal knowledge (Doran, 1978; Wellington, 1998; Leite, 2000). The same applies to the diverse types of investigations (Gott & Duggan, 1995). Hence, the types of knowledge that can be legitimately evaluated depend on the types of activities used for teaching and learning and the way they are used (Geli de Ciurana, 1995).

As far as laboratory investigations are concerned, it was argued above that they require and promote the development of conceptual, attitudinal and procedural knowledge. Arguments were also given for the laboratory procedure to be carried out by the students, at least when investigations are at stake. This means that psychomotor skills and accuracy in the performance of lab techniques may be evaluated. Thus, if investigations are carried out in science classes all those types of knowledge can be evaluated. Conceptual knowledge required or originated from investigations can be evaluated through conventional techniques (e.g. written tests) that are already familiar to the teachers. As investigations are unique opportunities to teach procedural understanding (Gott & Duggan, 1995), procedural knowledge is the most important type of knowledge to be evaluated within the scope of investigations. However, it may be a novelty and constitute a challenge for teachers both in terms of content to be evaluated and in terms of approach to its evaluation. On the other hand, it should be stressed that attitudes are difficult to evaluate and hard to change. Therefore, they may be better evaluated in terms of evolution over a period of time rather than by comparison with some type of criterion. As implicit knowledge cannot be specified it cannot also be evaluated as such although it will influence the overall judgement of the performance in the investigation. The comparison of the overall performance on the investigation with students' explicit knowledge may give some hints on students' use of implicit knowledge. Table 1 shows the techniques needed to evaluate the diverse types of knowledge involved in an investigation. Conceptual knowledge is usually evaluated whatever the teaching resource used to help students to acquire it. However, conceptual knowledge associated to investigations may be evaluated through the traditional means, before the investigation to diagnose their previous understandings and after the investigation to evaluate the conceptual learning outcomes. Non-conventional techniques can also be used along the phases 1, 3 and 4 to continuously evaluate students' conceptual understanding. Documents produced by the students can give some information about their conceptual knowledge and the validity of the information so collected can be improved by interviews focusing on the content of those documents or on other relevant aspects. Attitudinal knowledge can be evaluated mainly by observation of students at work. However, analysis of documents produced throughout the investigation activity can also provides some information on attitudes like rigor, and creativity. Nevertheless, it can hardly lead to distinguishing the different students in a work group. As far as the evaluation of procedural understanding is concerned, there are some differences between the investigation phases in terms of the most appropriate evaluation techniques. In phase 1 interviews and analysis of documents produced by the students can inform about students' procedural decisions relative to the pre-laboratory planing phase. Observation of students implementing the laboratory procedure is the main evaluation technique to be used during the laboratory phase 2. However, the register of data they produce can also be analysed and evaluated. During phase 3 students have to handle and interpret data collected, to evaluate them and to either propose reformulation or conclude from data. Thus, like in phase 1, interviews and analysis of documents produced can be used to evaluate students' understanding of the procedural contents under question in phase 3. In phase 4 synthesis and communication skills can be evaluated by means of analysis of the documents produced to divulge the investigation performed and by interviews focusing on them. The presentation and communication skills may also be evaluated through the observation of the presentation and an interview about why they did or reacted as they did during the presentation and public discussion of the investigation can provide valuable information. The self- and peer-evaluation documents elaborated by the students with regard to the eventual evolution of their procedural knowledge and attitudes can also be analysed in this final phase of the investigation. The discrimination of the types of knowledge and contents to be taken into account for evaluation purposes is an aid for teaching purposes and helps to clarify our thinking. However, it has to be seen alongside with tacit knowledge and students' attitudes, which also influence students' overall performance.

Final remarks

The evaluation of students' learning from investigations is not an easy task but learning taking place in labortaory environments needs to be evaluated if learning about the methods and processes of science is to be valued by students. The distinctive features of laboratory investigations imply that learning from investigations can only be evaluated within the context of an investigation, in a holistic way. They also make it hard to objectively evaluate students' learning in all the relevant components of knowledge involved. The complexity of this type of laboratory activity and the time it consumes leads to a rare use of it. Formative evaluation can (and should) be conducted whatever the number of investigations performed. On the contrary, for teachers to have legitimacy to evaluate students' investigative abilities with summative purposes they need to give students the opportunity to engage in several investigations. The pedagogical relevance of laboratory investigations justifies the investment needed to overcome conditions lacking nowadays in many schools so that students can gain experience and confidence in approaching scientific problems. As Woolnough (1991) states, "if we can leave our students with a sense of self-confidence in their ability to tackle scientific problems and have stimulated them by the fun and challenges of science, we will have equipped them with vision and a pair of stout boots well prepared to deal with the next unexpected challenge" (p. 188). Appropriate evaluation surely facilitates the attainment of this goal.

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Biography

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