Students' perceptions of when conceptual development occurs during laboratory instruction

Daniel S. Domin

Department of Chemistry, Tennessee State University, Nashville, TN, USA
E-mail: ddomin@tnstate.edu

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Abstract: Seventeen first year students experienced the first semester of laboratory instruction of a year-long sequence of general chemistry in a problem-based format, followed by a semester in which the laboratory portion of the course was taught in a traditional manner. At the end of the second semester all the students were administered a questionnaire regarding their perceptions of the different laboratory instructional environments. Fifteen of the seventeen students participated in semi-structured interviews. Analysis of the surveys and interview transcripts showed that seven of the students interviewed believed that the problem-based environment helped them better understand course concepts relative to traditional laboratory instruction, whereas the same number found them to be equally effective. Further analysis of the interview transcripts revealed that different students perceived conceptual development to be occurring at different times during the various types of instruction. For problem-based learning, conceptual development was maximized during the activity while in the laboratory. In the expository environment, however, it was maximized outside of the laboratory, after the experiment had been completed. Both the instructional and research implications of this phenomenon are discussed. [*Chem. Educ. Res. Pract.*, 2007, **8** (2), 140-152]

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Introduction

A clear and ever-present concern among science educators is what can be done with science laboratory instruction to improve student learning. Throughout its history, the science laboratory has been recognized as a unique instructional environment (Schwab, 1962; Hurd, 1969; Hofstein and Lunetta, 1982; DeBoer, 1991) and, while it shares many of the same goals and objectives for student learning as general science instruction, this unique structure allows students to engage in processes of investigation and inquiry in a manner not unlike actual scientists (Hofstein and Lunetta, 1982). As a result, this mode of instruction carries with it the expectation that student learning will be more meaningful than with other forms of science instruction (e.g., didactic lectures, demonstrations, museum exhibits, etc.). Unfortunately, as it is traditionally structured, science laboratory instruction has the enduring reputation of failing to live up to this expectation (National Research Council, 2006). As Roth (1994) succinctly put it, "*although laboratories have long been recognized for their potential to facilitate the learning of science concepts and skills, this potential has yet to be realized.*" (p. 197)

Consequently, throughout its history, alternative styles of instruction have been utilized in an effort to improve student learning. Domin (1999), for example, described, in addition to the traditional expository instructional method, three other commonly used styles of instruction: discovery (guided-inquiry), inquiry (open-inquiry), and problem-based. Although these other styles are often lumped together under the single rubric of non-traditional instruction, each is distinct and situates the student within a unique learning environment.

It is my contention that the perennial failure of science laboratory instruction to achieve its recognized potential stems from a lack of in-depth understanding regarding the constraints these different laboratory instruction styles impose upon the instructional environment and on the learning process. This study, therefore, attempts to partially alleviate this deficiency by addressing the perceptions students have as to how two different instructional styles, expository and problem-based, constrain conceptual development. In this paper, I discuss how such investigations can provide a deeper insight into how different laboratory instruction styles constrain the learning process. The implications from this affect not only the practical aspect of science laboratory education, but research in this area as well.

Background

Science laboratory instruction: traditional versus non-traditional

Science laboratory instruction is often presented as a dichotomy of styles, the exact label usage varying with the times. The most predominant manner of instruction is the traditional style (also commonly referred to as expository, deductive, or cook-book). This style relies almost exclusively on laboratory manuals to create a situation where students perform the activity by following a prescribed procedure to experience a pre-determined outcome. The other is the non-traditional style (also called student-centered, inductive, or inquiry). This, non-traditional, side of the dichotomy is actually a collection of different styles often grouped together because they share the same superficial characteristic of not being the traditional style.

Dichotomies are a fundamental attribute of human reasoning. They are a useful means of imposing order on something that is not well understood (Levi-Strauss, 1969). Dichotomous thought, however, suffers from two significant shortcomings. First, dichotomies are often based on superficialities; consequently, the understanding derived from the dichotomy is also superficial. Second, there is a propensity to exalt one element of the dichotomy over the other, resulting in one element being strongly advocated while the other is disparaged. In the context of science laboratory instruction this is expressed in the following mind-set: there exists a single best style of laboratory instruction (inquiry) and comparative studies are needed to simply confirm what is already known.

Comparative investigations between different styles of laboratory instruction are decades old and, despite claims to the contrary (Spencer, 1999), have yet to establish the supremacy of one style of instruction over another. For example, a meta-analysis conducted by Rubin (1996) found significantly improved student learning with non-traditional laboratory instruction relative to traditional laboratory instruction. Babikan (1971), on the other hand, found traditional laboratory instruction more effective than discovery learning with respect to overall achievement. Furthermore, a meta-analysis by Lott (1983) determined essentially no difference in overall student learning between the two approaches, although different styles did prove to be superior with respect to achieving specific learning outcomes.

Focusing on specific learning outcomes, however, also gives mixed results. Whereas Rubin (1996) found non-traditional forms of instruction superior in every respect: content knowledge, reasoning ability, attitudes, and manipulative skills, Lott's (1983) analysis showed non-traditional instruction to be superior with only content knowledge and understanding the process of science. The learning outcomes of 'problem-solving skills' and 'applying what has been learned' showed effect sizes favoring traditional instruction.

Blosser (1983, 1988), citing a number of methodological defects, cautions the reader against placing too much credence in comparative research studies. Such methodological defects include inadequate research design, inappropriate statistical treatment of data, small sample size, limited amount of time gathering data, inappropriate assessment instruments, and single studies with no follow-up of those who participated in the study. She stresses that comparative studies frequently are first-attempts at research conducted by graduate students pursuing a doctoral degree. And, she adds (Blosser, 1983), while many comparative studies describe the experimental treatment (usually non-traditional instruction) in great detail, the "*readers are often left to their own devices to determine what took place in the traditional approach* . . . ." (p. 167). This concern was also raised by Lott (1983).

An alternative taxonomy for science laboratory instruction

The inadequacies of the dichotomous paradigm are summed up very nicely by Reigeluth (1987) who, in his analysis of comparative research studies, stated the following:

> "*As with other disciplines, initial research on instruction tended to focus on very general, vague variables, such as discovery versus expository methods, and lecture versus discussion formats. However, in that research two different discovery methods often differed more than an expository and a discovery method differed, making it impossible to identify reliable causes of superior outcomes*." (p. 3)

A deeper understanding of the instructional dynamics associated with science laboratory instruction can be achieved by abandoning the current dichotomous way of thinking about science laboratory instruction in favor of a taxonomy where the non-traditional label is recognized as a collection of individual instructional styles. That is, non-traditional laboratory instruction is more usefully construed as consisting of three distinct instructional styles: discovery (guided inquiry), inquiry (open-inquiry), and problem-based (Domin, 1999). Each of these styles is unique, and distinguishing one from another, as well as from the traditional style, is achieved through a set of three descriptors: the approach taken, whether the outcome is known or unknown, and the origin of the procedure (Table 1).

Table 1. Descriptors for the laboratory instruction styles in Domin's taxonomy.*

	Descriptor		
Style	Outcome	Approach	Procedure
Expository	Predetermined	Deductive	Given
Inquiry	Undetermined	Inductive	Student Generated
Discovery	Predetermined	Inductive	Given
Problem-based	Predetermined	Deductive	Student Generated

* From Domin (1999).

The approach taken in a science laboratory activity is characterized as being either inductive or deductive. In an inductive approach, data is collected and general principles are derived from analysis of the specific phenomenon observed. The inductive approach is unique to discovery and inquiry style activities and is associated with initial concept formation. In contrast, the deductive approach proceeds from the opposite direction. Students are first exposed to the general principle, and then experience a specific episode in which the principle is evoked. In a deductive approach, the activity is intended to further conceptual development of something learned previously. Traditional expository instruction and problem-based activities extensively use a deductive approach.

Students can begin a laboratory activity either by knowing what constitutes the end of the experiment or they can come to that realization as they work through the activity. In the former, the outcome is regarded as predetermined, and in the latter it is undetermined. Expository, discovery, and problem-based activities are characterized as having predetermined outcomes (in a discovery-type activity, the outcome may already be known to the instructor, but not necessarily to the students; for them, the outcome could be undetermined). In an inquiry activity, the specific outcome is initially undetermined. The students begin without knowing the specific concept or principle that will be invented or discovered. It remains undetermined until the students are well into the activity.

Finally, there is the procedure. In the cases of expository and discovery activities, students are given the procedure to follow. Usually, it is part of an activity within their laboratory manual, but it may also be supplied to them as a handout or be provided directly from the instructor. Regardless of how it is presented, the students are expected to perform the activity as it is prescribed in the procedure. In contrast, in inquiry and problem-based activities, the students are responsible for generating their own procedure.

Traditionally, comparative research studies have generally assumed that there is a single best method of instruction, and the purpose of the research is to empirically establish one style as being superior. These research findings would then be used as the basis for advocating a particular style of instruction as *the* manner of instruction (Spencer, 1999; Monteyne and Cracolice, 2004). Adopting a taxonomy of four styles instead of two immediately does away with the notion of a single best style of instruction, for it is hard to identify any single style as being the best at achieving every possible learning outcome. In fact, a more useful mind-set is to presume that there are at least four different styles of instruction, none of which is the best at achieving all of the desired outcomes. Instead, it is presumed that the different styles possess their own unique strengths and weaknesses and constrain the learning environment in different ways. Different styles, therefore, should be better at facilitating the fulfillment of different outcomes. Research, then, should be conducted not to determine which style is the best, but rather to ascertain the different constraints each style imposes upon the learning environment. Through a better understanding of the dynamics and constraints associated with each style a more effective laboratory curriculum can be developed.

As stated earlier, studies pertaining to laboratory instruction styles have focused predominantly on determining which of two different styles is a better form of instruction. Comparison studies for the sake of better understanding instructional constraints are uncommon. One example, a study conducted by Shepardson (1997), compared student thinking processes exhibited in an expository environment to those exhibited in an open-inquiry environment. Because the former utilized primarily a deductive approach and the latter an inductive approach, differences between the two should be expected. This is just what Shepardson found; the thought processes exhibited by students in the expository laboratory tended to relate more to procedural issues, whereas student thinking in the open-inquiry environment related more towards data analysis and making sense of the results.

Purpose

In their most recent analysis of the laboratory in science education, Hofstein and Lunetta (2004) advocated more intensive research on the effect of science laboratory instruction on, among other things, the development of students' conceptual understanding. They stated that "*to acquire a more valid understanding . . . science educators need to conduct more intensive, focused research to examine the effects of specific school laboratory experiences and associated contexts on students' learning. The research should examine the teachers' and students' perceptions of purpose, teacher and student behavior, and the resulting perceptions and understandings (conceptual and procedural) that the students construct*". (p. 33)

The purpose of this study is to understand student conceptual development better in the context of science laboratory instruction. It involves a post-hoc analysis of student perceptions of learning in both problem-based and expository laboratory environments. However, it is not a comparison study in the sense of trying to determine if one style is better than the other; rather, it is a means of elucidating the constraints the two styles of instruction impose upon the conceptual development of the students. The presumption is that a better understanding of how students perceive the two environments with respect to facilitating conceptual development will offer valuable insight towards the development of more effective laboratory instruction.

Theoretical framework

This study was conducted within the theoretical framework of phenomenography (Barnard et al., 1999). That is, it attempted to elucidate from the students their understanding of their experiences within a general chemistry laboratory curriculum. Phenomenography takes the theoretical stance that different people will not experience a given phenomenon the same way (Orgill, 2007). Rather, it assumes that there are a finite set of ways in which different people experience a given phenomenon (Marton, 1986). The role of the researcher in a phenomenographic study is to describe the variations in understanding of a set of participants experiencing a particular phenomenon to establish a collective meaning (Barnard et al., 1999). This is achieved exclusively through participant self reports, primarily through interviews (Orgill, 2007). These interviews may or may not be supplemented with other forms of self reports such as surveys. Besides being essential to phenomenographic studies, self reports are considered a common method of data generation for a number of different types of qualitative inquiries (Lawrenz et al., 2003) and possess the following identified strengths (Fraser and Walberg, 1981; Huffman et al., 1997):

- Students' perceptions are based on the complete experience, not just on a limited number of observations.
- The perceptions of all the students participating in the self reports can be pooled.
- What the student perceives may be of more significance than what an outsider would observe.
- Student perception data can be analyzed to provide information about the perceptions of different students within the same class.

Methodology

Design

Data collection took place at a small rural two-year college in the Midwestern part of the United States. Seventeen students participated in two semesters of a first-year undergraduate general chemistry course designed for science majors. Both semesters included a laboratory component as part of the curriculum; one semester comprised entirely of problem-based activities, and the other expository activities. The topics covered within the laboratory activities during both semesters are best described as typical for a general chemistry curriculum (titrations, gas laws, Hess's law, etc.). However, each semester had a different laboratory instructor. The author of this paper served as the instructor for the problem-based semester and had the students work in groups of three or four. The instructor for the expository semester had the students work in pairs.

The first semester employed the problem-based format. The pre-lab activity consisted of students being given a problem statement one week prior to working on the problem in the laboratory (see Figure 1 for an example). As part of the problem statement, the students were directed to read pertinent chapters of the course textbook and develop a procedure that would allow them to solve the problem. During the in-lab activity, students worked cooperatively on developing a viable procedure. All procedural information and data were recorded in laboratory notebooks. While the students were working in the laboratory, the instructor was available to interact directly with the small groups. These interactions consisted of answering questions, addressing safety issues, demonstrating how to use specific equipment, and utilizing a Socratic method to guide the students toward a viable solution path. The post-lab activity consisted of writing individual laboratory reports.

Figure 1. An example of a problem statement given to students during the fall semester.

Analysis of a Calcium Supplement

Calcium, in the form of calcium phosphate, makes up a large part of the mineral matter of bones and teeth. An inadequate supply of calcium in the diet of growing children results in poor skeletal development. Pregnant women who do not consume enough calcium may experience a softening of the teeth and bones. Older women need a large amount of calcium in the diet to offset calcium loss in bones, a condition known as osteoporosis.

A well balanced diet rich in dairy products and leafy vegetables usually provides an individual with all the calcium they will need. However, it is quite often the case that people are unable to supply enough calcium through their diet to satisfy their needs. Because of this, calcium supplements are available at many drug and health stores. The calcium in these tablets is usually in the form of a salt: typically calcium carbonate or calcium lactate.

Your group will be given a calcium supplement in the form of $CaCO_3$. Your project will be to determine the mass of Ca^{2+} in a single tablet of the calcium supplement. Your value must contain at least 3 significant figures. You will have two lab periods to complete the activity.

Make sure you have read Chapters 1 - 4 of your text before coming to lab next week.

The laboratory activities during the second semester utilized an expository approach. The experiments came from a commercially available general chemistry laboratory manual and each activity conformed to the following traditional instructional format: pre-lab questions pertaining to the methodology and theory behind the activity, a procedure to follow in order to complete the activity, and post laboratory questions which had to be answered and submitted as part of a written laboratory report. Before each activity, the instructor held a class discussion to go over safety concerns and to demonstrate the proper use of the equipment being used that day.

Procedure

Students were informed in the middle of the fall semester that the next semester there would be a change in the manner in which laboratory activities would be addressed. Instead of following a problem-based format, the style would be expository. They were asked to pay attention to the differences between the two styles and, if willing, communicate their perceptions during semi-structured interviews. At the end of the second semester all the students completed a survey regarding their laboratory experiences (see Figure 2). The surveys were anonymously completed without either instructor being present.

Fifteen of the seventeen students (seven women and eight men) volunteered to participate in interview sessions with the author during the last week of the spring semester. The interviews were conducted on a one-to-one basis between each participant and the researcher. The interviews were semi-structured. That is, the participants were asked to answer in more detail the questions that appeared in the survey, but the researcher frequently asked additional questions that arose during the participant's response to the survey questions. Each interview was audio-taped and transcribed.

Figure 2. Survey questions given at the end of the spring semester.

Laboratory Evaluation

The laboratory component of this course differed from what you experienced last semester. This semester's lab style is usually referred to as a more traditional form of instruction, whereas the fall semester style is referred to as problem-based. Because you had the unique opportunity to experience both styles of instruction within a single academic year, your opinion of these two methods is very valuable.

Please take some time to complete the following survey and return it to your course instructor. The survey is confidential and should be anonymous (please do not write your name on the survey). Your cooperation and input is very much appreciated.

For each set of statements, indicate which best represents your opinion of the traditional lab style (T) and which best represents your opinion of the problem-based style (P).

1. ___ a. I learned a lot of new chemistry principles in this lab.
   ___ b. I didn't learn anything new from this lab.
   ___ c. I didn't learn anything new from this lab, but it did help me develop a better understanding of the concepts presented in lecture.
2. The topics we addressed in lab were . . .
   ___ a. well beyond our understanding (too hard).
   ___ b. well below our level of understanding (too easy).
   ___ c. hard enough to be challenging, but not impossible (just right).
3. The topics and/or problems we addressed coincided well with the material we were learning in lecture.
   ___ a. agree
   ___ b. disagree
   ___ c. don't know
4. The number of people I worked with in lab was . . .
   ___ a. too large.
   ___ b. too small.
   ___ c. just right.
5. The lab format provided me with a better understanding of what it is like to do real science.
   ___ a. agree
   ___ b. disagree
   ___ c. don't know
6. Given the choice, in the future would you prefer the traditional style of instruction or the problem-based style of instruction you had during the fall semester. Why?
7. Please comment on what you liked, did not like, and what you would change about both styles of laboratory instruction.

Results and discussion

Students' preferences

Originally, it was expected that the analysis of the collected data would lead to the identification of preferences students had toward the instructional environment. Such data would help the instructor make more informed decisions as to how the laboratory curriculum should be structured to better facilitate learning. The results of the survey and interviews showed that seven of the fifteen students perceived the problem-based laboratory to be a better learning environment, and another seven felt they were equally good, but in different ways. Only one student preferred an expository laboratory curriculum.

Students felt more cognitively engaged while performing an activity in a problem-based environment than in an expository environment. Statements such as "*you have to think about* *how you are going to conduct experiments*" and "*it allows more creativity*" are representative reasons students communicated in the surveys and interviews for preferring problem-based over expository instruction. The most cited reason, however, for favoring problem-based instruction was the cooperative approach employed. Because this was not a controlled factor for both styles of instruction, it cannot be certain if it is the high level of cognitive engagement associated with problem-based learning that made it more appealing, or students simply preferred to work in groups. This, and the possibility of students feeling pressured to say things that they think would please the instructor, severely compromise any conclusion drawn regarding the preference of one style of instruction over another.

Conceptual development

A critical attribute of qualitative research is the richness of the data set, which allows for the emergence of themes not originally considered during the development of the study, what Patton (1990) describes as "*the fruit of qualitative inquiry*" (p. 14). The original working hypothesis for this study was that students would have a clear preference for one style over the other. This was true for 53% of the students interviewed (seven preferring problem-based and one preferring expository). The other 47%, however, held no preference for either style. Although this sub-set of participants held no preference, it was clear that they did not hold identical perceptions of both instructional styles. During the analysis of student survey responses and interview transcripts it became evident that the students perceived the two environments differently with respect to facilitating conceptual development. This is reflected in the following interview exchange:

> I (Interviewer): *"Did any style help you learn the concepts better?"*
> P (Participant): "*Learn the concepts better? I can't really, I think I would say each one helped me learn the concepts. In different ways, but I would say both of them."*
> I: *"How were they different?"*
> P: *"The first one [problem based] took a little bit more figuring out. Whereas the second one* [expository], *uh, just basically took reading, consuming knowledge. Basically what they told you."* (participant 12, interview)

Other students were able to articulate a temporal dimension as being a critical difference between the two styles in promoting conceptual development. For example, the following survey statement indicates that this student perceived the traditional laboratory as an environment with low cognitive engagement and suggests that with expository instruction understanding develops primarily outside of the laboratory:

> "*I think that the 'cook book' lab style [expository] is a little boring, but for a student that had no background whatsoever of chemistry it might be a better start . . . . I liked the fact that no time was wasted. You did what you had to do and you were done. I didn't like the fact that you were not really challenged at the experimenting time, but on certain days I was not in the mood to be challenged so I could think about the results at a later time when I was ready to.*" (anonymous, survey response)

Expository laboratory activities are well-known by both instructors and students as capable of being performed with little preparation or engagement on the part of the student. If the student is 'not in the mood' to learn at that time, he need only go through the motions and collect the data. Later, when (if) he feels up to it, he can try to understand what the lab activity was all about.

The idea of conceptual understanding occurring outside of the laboratory after the activity has taken place is further supported by comments from other students:

> I: "*Did any style help you learn the concepts better?*"

P: *"In the second semester [expository] . . . I mean, I don't, I would really have no understanding until weeks afterwards of what we did."* (participant 15, interview)

Another student stated,

"The cook-book [expository], I really didn't get much understanding . . . If I did, you know and it tended to be well after the fact. Maybe, there may have been a problem that paralleled the lab in the book, perhaps." (participant 10, interview)

In this particular example, understanding for this student deepened when she was able to associate what was done in lab with another part of the course, in this case solving textbook problems. Additional exposure to the material at a later time facilitated conceptual development.

Students' perceptions were very definite as to when they began to understand material covered in the laboratory. In the expository environment, understanding developed outside of the laboratory after the activity had taken place. For some, it occurred by working out problems related to the material covered in lab; for others, it occurred while writing the laboratory report:

I: *"I think I understand. Now, . . . which gave you a better understanding of the chemistry concepts?"*
P: *"Yeah, but I could go without it you see. You know just going in and doing the stuff without it being a problem. Solving the problem, just gives you a fresh look."*
I: *"Does that come from reading the lab experiment before or while you are doing the lab? The lab manual, did that help you understand?"*
P: *"Uh, yeah doing lab you learn. A new lab . . . reading it before. I could understand. The traditional lab learned a lot more, especially the lab reports. I went way more in-depth the second semester."* (participant 2, interview)

Some students indicated that in an expository environment they felt the most significant part of their understanding occurred after the activity, when they had time to reflect:

I: *"How about the spring semester"* [expository]?
P: *"That was uh, obviously easier to know what you were doing as far as procedure again, because it was all cook-book. It was easier to figure out. Actually, you didn't even have to think about it, you did what it said and after you could reflect on what you just did and put it all together, after it was all done, after what has happened. And there was explanations as far as what chemical equations are pertinent to the experiment that would have been missed in the problem-based style."* (participant 12, interview)

Other student responses referred to being physically present in the laboratory, actually doing the activity, as a necessary condition for learning in a problem-based environment:

I: *"Do you think you could complete a lab experiment from either semester without having to go through lab"* [inaudible].
P: *"Yeah, the spring semester* [expository] *you could probably do it, just by reading the directions, but the fall semester* [problem-based] *you had to actually go to the lab."* (participant 13, interview)

Regardless of the style of instruction employed, students need an opportunity to think if understanding is to develop. Thinking engages the students. They reflect on what they have experienced, identify inconsistencies between their experiences and what they already know (cognitive dissonance), and attempt to alter their conceptual scheme in order to accommodate the new experience. Without students being provided the opportunity to think, their new knowledge stays rote knowledge with no further conceptual development. All instructional activities require a time for thought and reflection if the learning is to be meaningful. For problem-based and expository laboratory instruction a key difference is when the students are most likely to think.

Students partaking in a problem-based activity were most cognitively engaged while they were in the laboratory conducting the activity. This is indicated by the use of the terms ‘frustrating’ and ‘challenging’ to describe the problem-based activities. These terms indicate that students were, at some point in the lab, in a state of cognitive dissonance which they had to think through to reestablish cognitive equilibrium. These adjectives were never used to describe any expository laboratory session. Rather, terms such as ‘boring’, ‘repetitiveness’, and ‘robotic’ – terms more closely associated with low levels of cognitive engagement – were used by the participants to describe the expository activities. This does not mean that students did not learn from the expository lessons; many felt that they did. It simply means that the two styles of instruction differ as to when the students perceived themselves to be more cognitively engaged. Whereas students perceived themselves to be more cognitively engaged during a problem-based activity while they were in the laboratory, in an expository lesson higher levels of cognitive engagement were perceived to occur outside of the laboratory, after completing the activity, when the students had an opportunity to reflect on the material.

Conclusion

This study expands the scope of knowledge related to how two styles of laboratory instruction constrain the learning process. Specifically, it identifies a fundamental difference between expository and problem-based instruction with respect to fostering cognitive development. Both styles utilize a deductive approach, thus both should be capable of affecting conceptual development. This is supported by the finding that 47% of the participants found the two styles to be equal with respect to helping them understand pertinent concepts better. With respect to conceptual development, the distinction between them appears to be temporal in nature. In the problem-based format, the participants were more aware of conceptual development occurring while they were in the laboratory, engaged in the problem-solving activity. For expository instruction, the participants perceived conceptual development to occur outside of the laboratory, after completion of the activity. This finding has implications not only for chemistry teaching, but also for research pertaining to science laboratory instruction.

Teaching implications

Effective laboratory instruction requires engaging the minds of the learners so that they can think about the instructional episode in such a way as to evaluate their understanding in relation to what is experienced. This involves creating opportunities for reflection (Tien et al., 2007), as well as argumentation (Driver, 1995; Osborne et al., 2004). Both are necessary, and to be effective they must be explicitly linked to a specific laboratory experience (National Research Council, 2006). When to implement them for maximal effect depends on the instructional style used.

In the case of expository instruction, the participants in this study perceived understanding to develop outside of the laboratory, after the activity was completed, when they had the opportunity to reflect on what they had done. This included during the writing of the laboratory report or doing end-of-chapter problems that related to specific concepts addressed during a specific laboratory activity. For expository instruction, the post-lab activity is crucial for conceptual development; it may be the only opportunity the students get to reflect on what was done in the lab. During the actual in-lab activity, students’ minds are engaged not on the underlying principles, but on the procedural aspects of the activity. The cognitive demand placed on working memory in trying to understand and follow the given procedure allows for little, if any, cognitive resources to be devoted toward thinking about the concepts involved in the activity. This is supported by past research. Pickering (1987), for example, found that trying to increase the cognitive engagement of the students while they were in an expository laboratory environment collecting data interfered with their ability to complete the activity. Pickering rationalized this in terms of a hypothesis proposed by Johnstone (1984) of a working memory overload. That is, there is too much information within the traditional laboratory manual which hinders the students' ability to separate important information from extraneous material. These findings are further supported by the work of Mulder and Verdonk (1984), who found that students in an expository environment were rarely capable of learning both manipulative skills and the corresponding theory simultaneously.

Post-laboratory opportunities to reflect on the laboratory experience can be presented a number of ways, and should prove beneficial for conceptual development as long as the students can explicitly relate the post-lab activity to the laboratory experience. These can include, but are not limited to, the following: (1) post-lab questions from the laboratory manual, (2) end-of-chapter problems from the textbook, (3) structured reflection during the lecture component of the curriculum so that students can understand how the material relates to a previously completed laboratory activity, and (4) writing laboratory reports. Research by Keys (2000) has shown that the process of laboratory report writing can stimulate science learning provided that "*the students actively deliberated and reflected on science content as part of the writing process itself*." (p. 687)

Argumentation strategies are not typically associated with expository laboratory instruction. This is a deficiency that must be overcome, and as the results of this study suggest, they should be implemented as some sort of post-lab activity. This could be achieved through whole-class discussions immediately upon completion of the activity, in a similar fashion to what is advocated in discovery-type activities (Ricci and Ditzler, 1991). Alternatively, argumentation can be incorporated with reflection as part of an in-lecture activity where the instructor leads a discussion about a particular laboratory episode. Students would not only reflect on what was done, but would also develop and communicate a specific position pertaining to the underlying principles that overlap the laboratory episode and the current lecture topic.

Post-laboratory opportunities for reflection and argumentation are also beneficial in problem-based instruction. However, the findings from this study suggest that a maximum effect will be achieved when opportunities for these are presented during the in-laboratory activity as the students attempt to solve the problem. In a problem-based activity, students work cooperatively to develop a procedure that will allow them to solve a problem. This involves a high level of cognitive engagement where the students oscillate repeatedly between episodes of reflection and argumentation as they construct their own ideas on how to solve the problem; develop arguments to convince not only their peers, but also the instructor of the soundness of their idea; and evaluate the suggestions and arguments of others.

Research implications

In light of the results of this study, past studies comparing the expository approach to other laboratory instructional methods must be re-evaluated. For any comparative study to have any contemporary relevance, it must be established that the students in the expository group were provided with the full gamut of instruction: a pre-lab to prepare them for the laboratory activity, the actual laboratory experience, and a post-lab activity that provides an opportunity for both reflection and argumentation. Failure to include any of these components seriously compromises the validity of a comparison study. The format utilized by Suits (2004) that provides the instructional approach, pre-laboratory preparation, type of experiments utilized, experimental work, type of post-laboratory activity, and method of assessment for both the control and treatment groups should be standard in any comparative study.

This study strongly suggests that expository and problem-based instruction constrain the process of conceptual development differently. Further research is needed to expand our understanding of other differences between laboratory instruction styles with respect to the constraints they impose upon other learning outcomes. Additionally, research should be undertaken to investigate the mutability of these constraints. For example, is it possible to restructure expository instruction so that student cognitive engagement is maximized during the laboratory activity instead of during the post-lab activity? Some research has been done in this area with some rather interesting results. Cox and Junkin (2002), for example, found that embedding conceptual questions into the procedure of an expository laboratory activity and allowing students to discuss these questions in a cooperative environment during data collection significantly increased student gains on tests of conceptual understanding. Further research in this area is strongly needed.

Finally, science educators and researchers must be aware that each style of laboratory instruction is different and possesses different constraints that will invariably affect how and to what extent specific learning outcomes can be achieved. Each style, therefore, must be evaluated in light of these constraints. Before certain styles of instruction are written off as being ineffective, educators need to be certain that the activities are being implemented in a manner that conforms to the constraints imposed by the employed style. This can only be done by better understanding the subtleties associated with each instructional style.

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