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STUDENTS' THINKING IN A CHEMISTRY LABORATORY

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ABSTRACT

Despite the almost mandatory inclusion of a laboratory component in the school curriculum very little has been reported about the effects of laboratory instruction upon student learning and attitudes. The present study was undertaken to investigate the thinking of students in a chemistry laboratory. An interpretive research method was adopted in collecting and analysing data gathered from observations, general interviews and stimulated recall interviews. Four high school students were studied during their participation in a week-long university summer school program. This study reports how the four students responded differently to the same laboratory experience.

INTRODUCTION

The inclusion of a laboratory component in science education had its origins in the 19th Century when chemical schools were established as training grounds for young practical chemists (Hegarty-Hazel, 1990). Since that time the rationale for including a laboratory component within a science curriculum has undergone many transitions. Hegarty-Hazel (1990) accounted for the origins and institutionalisation of laboratories for the teaching of science. Initially, training in practical skills was the principal goal; then there was a shift to teaching the scientific method. However, factors including a lack of resources and a shift in accepted philosophy meant that laboratory experiments became graded exercises from structured manuals. The educational reforms of the 1960s produced inconsistent and contradictory frameworks for science curricula resulting in teaching laboratories plagued with problems (Hofstein & Lunetta, 1982). Many science experiments in high schools required students to follow strict instructions, recipe-style. Deviations from the instructions were not tolerated lest the experiment might fail. This cookbook approach to science experiments has been linked to an objectivist view which apparently underlies much science teaching practice (Tobin, 1990a). Objectivists hold that knowledge exists independently of the knower and is transferred from an authority to a passive learner. Many studies report findings that question the effectiveness of traditional teaching methods and routine, passive practical work (Gallagher & Tobin, 1987; Tobin & Gallagher, 1987). The cookbook approach is not particularly effective in promoting conceptual understanding except for a very small proportion of pupils (Hodson, 1993). Evidence exists that suggests many students, even after successfully completing basic science courses, still misinterpret many of the scientific concepts ostensibly learned by them (Reif & Allen, 1992).

Ritchie (1994a) described constructivism as an epistemology which focuses on the role of the learner in the personal construction of knowledge. From this perspective learning is viewed as an adaptive process where the learner's existing knowledge is modified in response to perturbations which arise from both personal and social interactions (Wheatley, 1991). Recognition that students construct and reconstruct their own beliefs through a process of negotiated meaning (Driver, 1988) has highlighted the need to incorporate appropriate laboratory exercises that foster this adaptive process.

Roth (1994) reported that students were aware of the difference between open-ended inquiry and traditional laboratory exercises and that most students did not like the cookbook approach because the purpose of most steps remained hidden from them. Johnstone and Wham (1979) found that students "were able to think for themselves and be actively involved in planning their own procedures" when engaged in open-ended inquiry laboratory work (p.17). The present study investigated the responses of different students to a research project conducted along the lines of an open-ended inquiry.

METHODS

Purpose

Gallagher (1987) concluded that "Laboratory work is an accepted part of science instruction. Given its important place in the education of youth, it is surprising that we know so little about its functioning and effects" (p. 351). The purpose of the present study was to document student thinking during laboratory activities in a setting similar to that of practising scientists and to add to the now growing literature on the value and nature of quality laboratory instruction. In particular, this study focused on the thinking of four different students as they engaged in the same open-ended chemistry project.

Setting

The study was conducted in a chemistry laboratory at a university located in North Queensland, Australia. The university conducts summer schools where Year 11 students are invited to take part in a university experience program designed to introduce high school students to the atmosphere of learning in a university. A supervisor, not one of the authors, guided the students through their chemistry project. This supervisor was a university lecturer with a PhD in chemistry who also held a secondary teaching qualification. The students' comments suggested that the supervisor was very good at explaining processes clearly and his style appeared to encourage student questioning and participation. The students had exclusive access to a fully-equipped third year chemistry laboratory and a technician was available to provide all glassware, reagents and materials.

Subjects

All four subjects were female and had just completed Year 11 at their respective high schools. Two were from the same private school and two were from public schools in different rural towns. All four had voluntarily elected to spend the last week of their school term at the university summer school.

Wanda was particularly skilful during laboratory sessions. She not only revealed that she had considerable prior experience in school laboratories but also appeared to be reflective and articulate during interviews.

Betsy had very limited experience in laboratory work and never became completely comfortable with the apparatus. However, she made valuable contributions to the group work and was able to articulate her thoughts without much difficulty.

Sandy was quiet and serious and although she had limited laboratory experience she soon assimilated the necessary skills for the project. Through time she appeared to become more confident in her own abilities. She made valuable contributions to the group but had some difficulty articulating her thoughts.

Jane was bubbly and talkative but also displayed limited laboratory expertise. She admitted to lacking the ability for reflective thoughts. During interviews she had great difficulty in articulating or even remembering her thoughts.

Project description

The project involved the quantitative analysis of phosphate levels in various water samples using spectrophotometry. Two methods of phosphate analysis were used, a standard method and the Greenpeace method. Although the project was presented to students as a mini-research project, it was not strictly an open-ended inquiry. However, the students gradually assumed greater responsibility for their progress throughout the duration of the project. For example, on Day 2 the students figured out the best range of concentrations to use in order to construct the standard curve on their own, rather than follow a set of instructions, cookbook style. The supervisor did provide explanations for theories and concepts but led the students through the process by questioning and probing rather than by simple delivery of facts. Consequently the students' level of ownership with the project was high. As Wanda described her thoughts when the supervisor left the students alone to work: "It was sort of like a new experience and you get really excited. It's sort of like 'Wow, you know, let's see if we can do this work' ..."

At the first laboratory session on Day 1 the supervisor explained the theory relating to the measurement of concentration by absorption. The process of creating a calibration curve was also explained and the students were told they were to compare the two methods of phosphate analysis.

Following the pre-laboratory explanation, the students were then allowed to proceed at their own pace. The supervisor was constantly available for help during this time and often demonstrated the use of apparatus to the students. The students' first task was to construct a calibration curve according to the standard method. This task took the remainder of the first day.

On the second day the students used the Greenpeace method to construct a standard curve and determine the concentration of some known samples. This task took the most of Day 2. The supervisor was again available for student consultation but was progressively allowing the students to own the project themselves.

On Day 3, the students were taken on a field trip to the sewage plant to collect samples. Inflow and outflow samples were taken. When the students returned to the laboratory, they used the two methods to determine the phosphate levels in the samples. The supervisor was absent during this time and the students were self-directed with access to a technician.

On Day 4 the students worked on preparing a poster presentation of their project. The poster was part of a public display of all projects undertaken during the summer school. Again the supervisor did not participate to a great extent in this process and the students took responsibility for the content and layout of the poster.

On Day 5 the students assembled their poster presentation. The supervisor suggested that the students might wish to construct a visual display depicting the mixing of the reagents which created the coloured solution measured by spectrophotometer. The students embraced this idea and spent a great deal of time working out the mechanics of such a display.

By the end of the week the students had gained hands-on experience with the concepts of spectrophotometry, calibration curves, concentrations, serial dilutions, and analysis of water samples.

Data sources and techniques

A researcher was present as an observer for most of the time the students worked in the laboratory. There was minimal interaction between the researchers and students during observation. The major source of data was stimulated-recall interviews conducted over the week to access students' thinking. Two interviews, approximately 30 minutes in duration, were conducted with each student to yield eight interviews overall. The stimulated-recall interview technique has been used in process-tracing research to study the mental functioning of people at work in various task environments, including expert physicians (Elstein, Shulman & Sprafka, 1978), counsellors and their clients (Kagan, Krathwohl, Goldberg & Campbell, 1967), teachers (Marland, 1979; Yinger, 1980) and school students (Marland & Edwards, 1986; Ritchie, 1994b). The principal guidelines outlined by Marland (1984) were followed in the conduct of the interviews which were designed to encourage and facilitate disclosure of student thinking. All stimulated-recall sessions were audio-taped and transcribed for subsequent analysis resulting in 70 typed pages of data. In addition, students were observed by the researchers over the week to provide descriptive profiles and general interviews were carried out to reveal students' backgrounds, attitudes and expectations. Analysis of the data was carried out in an interpretive style, similar to that described by Erickson (1986). More specifically, assertions were generated from the data during the fieldwork phase and were later revised and modified through induction following a rigorous search of the data base. These assertions were checked against both confirming and disconfirming evidence to provide an interpretive analysis of the data.

DISCUSSION OF RESULTS

Two general assertions emerged from the analysis of the interview transcripts. Firstly, the lack of laboratory skills apparently interfered with conceptual learning and secondly, the relevance of the project promoted student interest. These assertions were supported by the descriptive profiles of the students generated by the observations and general interviews and will be discussed below with reference to students' experiences over the course of the project.

Assertion 1: Lack of laboratory skills interfered with conceptual learning

Wanda was by far the most competent in laboratory skills and frequently took the initiative on Day 1 when the students were setting up their first calibration curve and were unsure how to use the glassware. On Day 3 when the supervisor left the students to work on their own, Wanda was instrumental in keeping the momentum of the group going.

> I was thinking how we could get things moving pretty much and I thought that maybe there was some way I could get some more funnels from out the back so we could get the filtering under way more quickly so we could get stuck into our measuring ... I think I said we should try and find some funnels and stuff so we could make it quicker and they said it was a good idea so Jane and I went out the back and got some.

Wanda also sensed that her expertise with glassware exceeded that of her colleagues. For example when Betsy was using a pipette on the first day:

W: [laughs]
I: What's so funny?
W: She [other student using a pipette] was always asking what the measurement was ... I was used to using [pipettes] because I use them at school all the time ... they [the other students] just learnt how to use them and how to read them.

It appears that Wanda's confidence with glassware allowed her to concentrate on the problem-solving aspects of the project and she subsequently emerged as the leader of the group. The other students often asked her for advice and once she even explained to the supervisor how to use the pipette safety bulb correctly when he was floundering. Although these examples highlight Wanda's superior laboratory skills, she was not dominating and her style of group behaviour was more negotiated and democratic. For example when Wanda was describing her thoughts whilst the group was figuring out the next stage of the project:

I: So are these your thoughts or are you getting thoughts from others?
W: Yes, they'd be pretty much my thoughts and I'm also conscious of everyone else's to make sure it's sort of ... we have the same sort of type of feeling within the group, because if we don't, someone could get confused.

Many researchers (Friedler & Tamir, 1990; Johnstone & Wham, 1982; Rubin & Tamir, 1988) have argued that inquiry oriented laboratory work is cognitively demanding and that students may suffer 'information overload' of their working memory capacity. Expert scientists cope in these situations because they have highly developed technical skills which allow them to participate in genuine scientific inquiry unhampered by poor technique (Hegarty-Hazel, 1990). There are many instances where Wanda reported she was thinking about conceptual aspects of the project, for example when she was trying to work out the best set of serial dilutions to use:

> Yes I'm wondering "What's that? What's it represent?" I'm trying to think and remember back to yesterday and the other solutions that we made up. We measured the colour and the concentration of it and I'm trying to work it out in my head where exactly that was [on the curve] and whether we need to dilute it more or whether it was OK.

and also when she was using the graphs to determine the phosphate concentration:

> Just going through my head are the processes that we've been through, Greenpeace and the other one. I was remembering the results we got from them. We had to draw up graphs from that and I'm trying to think in my head which onè was more linear, which was more accurate.

In comparison, the other students spent far more time thinking about getting the skills right and reported few instances of conceptual thinking. For these students, the use of pipettes was a new experience and clearly they were hampered during the early stages of the project by their inferior techniques. For example, Jane commented: "We do pracs [at school] but like we've never used a pipette. Pracs usually relate to our topic but we don't mix chemicals like we've been doing."

Jane constantly referred to her lack of ability in the laboratory. She was often heard to say "If something's going to go wrong, I'll be the one to do it" and frequently sought confirmation from other students or the supervisor before proceeding. Jane's lack of confidence in laboratory techniques led her to engage consistently in a number of strategies to avoid doing tasks that she felt unable to perform successfully. Johnstone and Wham (1982) identified a number of strategies students may engage in when learners suffer cognitive overload. Two strategies in particular - exhibiting random behaviour, in which she was "very busy getting nowhere", and becoming 'helper' or assistant to a group organised and run by others - were adopted by Jane throughout the course of the project.

Betsy was also hampered by her inadequate technique at the start of the project and also engaged in avoidance strategies. When Wanda was using the glassware to measure out reagents Betsy described her thoughts as follows:

B: More than anything I was sort of like organising everything for her [Wanda] to do, the measuring and things like that.
I: So Wanda was doing the hard work?
B: No, ... well, Wanda had the pipette.

and also when Betsy undertook the task of setting up a filtering apparatus she reported her thoughts as:

> I'd never learnt how to fold a filter paper and I was thinking I didn't have a clue how to do it and also I was putting water all over the filter and I was worried about that and I was being careful not to contaminate the stuff. I was just about to ask her [Wanda] when she finished washing.

Obviously Betsy's thinking was preoccupied with getting the techniques right. However, as time progressed Betsy became far more confident and, through experimentation, mastered many laboratory techniques:

> I was just checking if it made any difference like if I had it [the filtering apparatus] above the beaker. I lifted it up and checked if it flowed through and it didn't, not noticeably, so I just left it.

Sandy managed to assimilate the required techniques quickly and was fairly confident in using her new skills. The lack of technical skills did not pose the same barriers for Sandy as it did for Jane and Betsy.

Assertion 2: Relevance of laboratory investigation promoted interest

Consistent with a number of studies pointing to the popularity of laboratory work in the high school years (Dawson & Bennett, 1981; Keightley & Best, 1975) all four students in the present study reported a liking for laboratory work. There were several aspects of the research project which students reported were superior to their regular classroom practicals. All students reported a high level of interest in the research project exemplified by the following comments from Jane and Sandy:

J: I didn't know what to expect when I came but it's been better than what I thought it would be. I think it's good because it's practical as well and you don't do things like this at school.

S: The last term we haven't done a lot [of pracs]. We've been learning more about the periodic table and molecular shapes and things so I haven't really done any pracs for about the last term, which is pretty boring ... It's different to what you do at school. At school you're more thinking about the work you are doing. And it's more working out problems, it seems more structured and you have set questions.

Fordham (1980) suggested that interest in laboratory work would be stimulated by increased cognitive challenge. Current science teaching may fail to engage students cognitively by favouring teacher-driven cookbook style exercises. Students subsequently regard the laboratory as "an alien environment of forbidding rituals, with little relevance to everyday life" (Hodson, 1993, p. 92). In contrast, the students in the present study frequently made reference to the relevance of their research project to "real life".

B: I didn't realise that it was this interesting. I liked chemistry at school but you don't actually see what the chemists do in real life, how they research and things like that.

S: The pracs you do at school don't have any purpose. They're fun but they don't have a purpose. Mostly [the project's] been pretty good ... There's a purpose in what we're doing. It's not just at school, sort of thing. You're researching something and so it's been good. It makes me like chemistry more and getting away from the classroom situation.

The students readily identified a distinction between the type of laboratory experience offered at school and that offered by the present research project. As well, all students reported a preference for the less structured approach of the research project. This evidence supports the claim by Hodson (1985, p. 44) that "much practical work in school is aimless, trivial and badly planned."

Wanda appeared to be very interested in the project and in analytical chemistry as a whole. When the laboratory technician happened to show the students a water sample from a sugar mill, Wanda keenly listened and asked questions:

> I was quite interested in this sample that she had because it came from a sugar mill and where I come from it's like pretty much cane and everything. My dad drives a harvester and is closely related to the cane industry anyway and I was quite interested because we're not educated much on what other metals or whatever you call it that is in samples and stuff so I was quite interested in what she had there.

In addition to high interest levels, the students reported that they welcomed the opportunity to relate theory to practice.

B: In school we don't get to practically use a lot of the ideas we're taught and a lot of stuff is more clearer [sic] now because you can see it in real life. You learn about theories and that and you can't put it into practice but here we've been using the machine [spectrophotometer] and we've learnt a lot we don't practically think about. When something happens, you think "Oh yeah, so this is what they've been talking about" - things like precipitation.

Atkinson (1990) reported that in school science the laboratory appears not to be providing the link with theory which had been expected. Constructivists maintain that learning is an interpretive process, as new information is given meaning in terms of the student's prior knowledge. Open-ended laboratory experiences allow students to learn with understanding (Tobin, 1990b).

The concept of working intensely on a project over a period of time appealed to all students and most referred to the freedom of time the research project allowed.

S: The stuff we do at school are pracs that can be done in half an hour. I probably enjoy this [project] more.

B: We had time to get to know each other and do our work at the same time ... Even if it was spread over more time, we could have done a lot more with it [the project].

Insufficient time to complete laboratory work is a common complaint in practical classes (Fordham, 1980) and one of the benefits of a research style project is the luxury of time. This luxury not only allows an experiment to be completed, but also affords the students plenty of time and opportunity to "reformulate their ideas, and to consider reasons for modifying and changing their frameworks of understanding" (Hodson, 1993, p. 111).

CONCLUSIONS

The 'Science For All' catch-cry currently popular in science education advocates making science accessible and meaningful to all students, not just for an elite group destined for a career in science. A commitment to science for all requires that science curriculum, teaching and assessment take into account student diversity and ways of coming to understand science. Data presented in this study suggest that some students are not suited to the open ended inquiry approach at the same time or at the same level. In his study of a high school laboratory course that was different from traditional science instruction Roth (1994) reported on the remarkable ability and willingness of students to generate research questions and to design and develop apparatus for data collection. Surprisingly, despite studying a total of 46 students, no instances where students failed to generate appropriate research questions or struggled to come to grips with the processes or concepts involved were reported. Roth appears to assume that the open-ended structure is best for all. Our study suggests that different students respond differently to the same laboratory experience. Mulopo and Flower (1987) have also shown that different styles of laboratory work produce different learning outcomes according to the developmental stage of the child and Hodson (1993) cited work by Strehle which suggested laboratory work produces much greater variation in individual performance than other teaching and learning methods. Hodson's (1993) call for researchers to focus more sharply on what students are actually doing promises to yield further insights into the pedagogic value of practical work.

This study identified two contributing factors for the differential response exhibited by students to the same laboratory project. Firstly, a lack of laboratory skills interfered with conceptual learning. As discussed by Friedler and Tamir (1990), inquiry oriented laboratories appear to be too difficult for many students. More specifically, demand for formal reasoning and the cognitive overload which results from the need to apply intellectual skill, practical skills and prior knowledge simultaneously provide substantial barriers to successful inquiry. Johnstone and Letton (1989) warn that since working memory capacity is limited, students need to control the amount of information they process. Hegarty-Hazel (1990) advocates teaching of procedural and substantive knowledge prior to any inquiry exercise in a structured and sequenced program. In contrast, Hodson (1993) favours on-the-job training in technical skills, perhaps with some kind of basic familiarisation program. Our results suggest that neither approach would serve the needs of all students. Instead, exposing students to a variety of learning situations is probably more likely to accommodate student diversity and satisfy the science for all policy.

The second contributing factor to the differential response in the students was that relevance of the research project promoted interest. All students reported a high level of interest in the project but for different reasons. Obviously there are many aspects to be considered in arousing and sustaining students' interest in a laboratory experiment.

Our study has highlighted the benefits of laboratory activities which are both relevant to students and designed to match student readiness for open-ended inquiry. The impact of the students' experience with open-ended inquiry on school learning will be the subject of subsequent investigations.

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