CHEMISTRY EDUCATION: RESEARCH AND PRACTICE
2004, Vol. 5, No. 3, pp. 247-264

INVITED SPECIAL SECTION: Contributions of Educational Research to the Practice of Chemistry Education
Laboratory and Practical Work

Avi HOFSTEIN
The Weizmann Institute of Science, Department of Science Teaching
(Israel)

THE LABORATORY IN CHEMISTRY EDUCATION: THIRTY YEARS OF EXPERIENCE WITH DEVELOPMENTS, IMPLEMENTATION, AND RESEARCH

Received 8 October 2004; in final form 1 November 2004

ABSTRACT: Since the 1970s', the author was involved in researching the laboratory work. The research focused on the various issues concerning the laboratory as a unique learning environment. Most of these studies are included in this review. They were mainly conducted at the Department of Science Teaching, *The Weizmann Institute of Science*, in the context of chemistry curriculum development, implementation and evaluation. The review of the research studies and its related publication is organized under the following key issues: (1) The chemistry laboratory: A unique mode of learning, instruction, and assessment. (2). Assessing students' performance and achievement using different modes of presentation in the chemistry laboratory. (3) Students' attitude towards and interest in school chemistry laboratory work. (4) Students' perceptions of the laboratory classroom learning environment. [*Chem. Educ. Res. Pract.*: 2004, *5*, 247-264]

KEY WORDS: laboratory work; assessment; practical-mode; laboratory learning environment; attutudes and interest

INTRODUCTION

Laboratory activities have long had a distinctive and central role in the science curriculum and science educators have suggested that many benefits accrue from engaging students in science laboratory activities (Pickering, 1980; Hofstein & Lunetta, 1982; Garnet et al., 1995; Lunetta, 1998; Tobin, 1990; Hofstein & Lunetta, 2004). Since the end of the 19th century, when schools began to teach science systematically, the science laboratory has become a distinctive feature of science education. In order to illustrate this, it is worthwhile to quote from Ira Ramsen (1846-1927), who wrote his memories as a child experiencing a chemical phenomenon:

> *While reading a textbook of chemistry, I came upon the statement, 'nitric acid acts upon copper'…and I [was] determined to see what this meant. Having located some nitric acid….I had only to learn what the words 'act upon' meant…. In the interest of knowledge I was even willing to sacrifice one of the few copper cents then in my possession. I put one of them on the table; opened the bottle marked 'nitric acid' poured some of the liquid on the copper; and prepared to make an observation. But what was this wonderful thing which I beheld? The cent was already changed, and it was not a small change either. A greenish blue liquid foamed and fumed over the cent and the table. The air… became colored dark red…. How could I stop this? I tried by picking up the cent and throwing it out of the*

window…I learned another fact; nitric acid… acts upon fingers. The pain led to another unpremeditated experiment. I drew my fingers across my trousers and discovered nitric acid acts upon trousers….I tell it even now with interest. It was revelation to me. Plainly the only way to learn about such remarkable kinds of action is to see the results, to experiment, to work in the laboratory. (Adopted from Gutman, 1940*).*

During the major curriculum reforms in science education in the early 1960s, practical work in science education was used to engage students in investigations, discoveries, inquiries, and problem-solving activities. In other words, the laboratory became (at least in the minds of science educators and curriculum developers) the center of science teaching and learning. For example, George Pimental editor of the CHEMStudy (summarized by Merril & Ridgway, 1969) suggested that the laboratory was designed to help students gain a better idea of the nature of science and scientific investigation by emphasizing the discovery approach. In addition, he suggested that it gives students an opportunity to observe chemical systems and to gather data useful for the development of principles subsequently discussed in the textbook and in class. However, when it came to assessing and evaluating the effectiveness of the laboratory, the situation was less simplistic and less clear. For example, as early as 1969, Ramsey and Howe, on the basis of an extensive review of the literature regarding instruction in the science laboratory concluded that:

The experience possible for students in the laboratory situation should be an integral part of any science course has come to have a wide acceptance in science teaching. What the best kinds of experiences are, and how these may be blended with more conventional class work has not been objectively evaluated to the extent that clear direction based on research is available for teachers. (p.75)

Between the 1960s and the 1980s, hundreds of research papers, essays as well as doctoral dissertations were published with the goal in mind of trying to explore and investigate variables and settings regarding the uniqueness of the science laboratory in general and its educational effectiveness in particular. These studies were critically and extensively reviewed (Bates, 1978; Blosser, 1980; Hofstein & Lunetta 1982). Hofstein and Lunetta's (1982) review provided perspectives on the issue of the science laboratory through a review of the history, goals, and research findings regarding the laboratory as a medium for instruction in secondary school science teaching and learning.

Ten years later, Tobin (1990) prepared a follow-up synthesis of research on the effectiveness of teaching and learning in the science laboratory. He proposed a research agenda for science teachers and researchers. Tobin suggested that meaningful learning is possible in the laboratory if the students are given opportunities to manipulate equipment and materials in an environment suitable for them to construct their knowledge of phenomena and related scientific concepts. In addition, he claimed that in general, research had failed to provide evidence that such opportunities were offered in school science.

More recently, Hofstein and Lunetta (2004) conducted a second analytical review of the literature and concluded that:

Clearly, serious discrepancies exist between what is recommended for teaching in the laboratory-classroom and what is actually occurring in many classrooms. Researchers need to examine and understand why large numbers of "good teachers" have not been using authentic and practical assessment on a regular basis. Such understanding should then shape research on classroom practice, the development of assessment techniques, teacher professional development, and further research studies. No doubt, the issues are complex, but explanations may lie in differences in the perceptions of teachers and researchers. For example, teachers may perceive they do not have the time or skill *required to implement such assessment methodologies successfully. Reluctance may also originate in the beliefs teachers hold about what students should be learning in laboratory experiences, how students learn, what they need to do to achieve important learning outcomes, and what they need to perform successfully on external examinations. Building on relevant scholarship, future research in science education should produce information that informs the development of strategies, protocols, and resources for teaching and for the professional development of teachers. Questions to be addressed include how to assess students' learning efficiently and effectively when they are engaging in inquiry and practical work, how to engage students with different skills and knowledge in practical experiences that result in meaningful learning, and how to promote a more effective laboratory learning environment.*

In 2004, as this review of my work is being written, we operate in a new era of reform in science education. Both the content and pedagogy of science learning and teaching are being scrutinized, and new standards intended to shape meaningful science education are emerging. The *National Science Education Standards* (National Research Council, 1996) and other science education literature (Lunetta, 1998; Bybee, 2000; Hofstein & Lunetta, 2004) emphasize the importance of rethinking the role and practice of laboratory work in science teaching in general and in the context of chemistry education in particular.

It is true that very often research has failed to show a simplistic relationship between experiences provided to the students in the laboratory and learning science. However, sufficient data do exist to suggest that the laboratory instruction is an effective and efficient teaching medium to attain some of the goals for teaching and learning science. Appropriate laboratory activities can be effective in helping students construct their knowledge (Tobin, 1990; Gunstone, 1991), develop logical and inquiry-type skills, as well as problem-solving abilities. They can also assist in the development of psychomotor skills (manipulative and observational skills). In addition, they have a great potential in promoting positive attitudes and in providing students with opportunities to develop skills regarding cooperation and communication. In this respect the science laboratory is a unique learning environment. Thus, it has the potential to provide science teachers with opportunities to vary their instructional techniques and to avoid a monotonous classroom learning environment.

Thirty years of experience in researching the chemistry laboratory

The review of my research on the laboratory is based on more than 30 years of experience with all facets of the chemistry curriculum in the upper secondary schools in Israel. This included chemistry curriculum development, implementation, evaluation, and research. Throughout the years an attempt has been made to cover most of the domains that characterize practical work in the context of the chemistry laboratory. Among these are studies focusing on the following aspects:

1. The chemistry laboratory: A unique mode of learning, instruction, and assessment.
2. Assessing students' performance and achievement using different modes of presentation in the chemistry laboratory.
3. Students' attitude towards and interest in school chemistry laboratory work.
4. Students' perceptions of the laboratory classroom learning environment.

THE CHEMISTRY LABORATORY: A UNIQUE MODE OF LEARNING, INSTRUCTION, AND ASSESSMENT

Kelly and Lister (1965), based on comprehensive research findings, suggested that the science laboratory is a unique mode of teaching and learning and that the abilities of students in the laboratory are only slightly correlated with their abilities in other non-practical learning experiences. Support for this was provided at a later stage by Tamir (1972) and more recently by Yeany, Larossa, and Hale (1989). A study on modes of learning and teaching in the context of chemistry was conducted by Ben-Zvi, Hofstein, Samuel, & Kempa (1977). The main goal of this study was to identify relationships between modes of learning in the chemistry laboratory and other modes of learning that prevail in high school chemistry. The study was undertaken in the context of a laboratory centered program: *Chemistry for High School* (1972), developed at the Weizmann Institute of Science. This program was developed and implemented in the Israeli education system to replace the adopted version of the CHEMSudy program. To this end, a battery of tests were developed to cover at least the first three phases of performance in the chemistry laboratory (Kempa & Ward, 1976; Kempa, 1986; Giddings & Hofstein, 1990; Giddings, Hofstein, & Lunetta, 1991): *planning and design* (formulating questions, predicting results, formulating hypotheses, to be tested designing experimental procedures); *performance* (in conducting an experiment, manipulating materials and equipment, making decisions about investigative techniques, observing and reporting findings); *analysis and interpretation* (processing data, explaining relationships, developing generalizations, examining the accuracy of data, outlining limitations, formulating new questions based on the investigation conducted); and *application* (making predictions about new situations, formulating hypotheses on the basis of investigative results, applying laboratory techniques to new experimental situations). These phases refer both to psychomotor skills (manipulation and observation) and to cognitive abilities, i.e. investigation and processing of a problem and its solution by practical means. The battery of tests included two practical tests using a scheme and criteria originally developed by Eglen and Kempa (1974), an observational test (Kempa & Ward, 1976), two paper and pencil achievement tests, and an attitude and interest questionnaire. This battery of tests was administered to a sample of 233, 10^{th} grade students (in 12 classes from 5 schools) in Israel. Correlation of the results followed by factor analytic investigation revealed the following:

- Cognitive achievement in chemistry measured by written paper and pencil tests and achievement in the chemistry laboratory constitute independent modes.
- Factor analytic investigation of the various variables showed that the practical domain can be subdivided into three distinct modes:
  - -problem-solving abilities;
  - -skills in performing routine laboratory tasks;
  - -the ability to observe.

Overall achievement in chemistry is therefore a combination of all these various modes that have to be taken into consideration when assessing students' ability in chemistry. Although this study was conducted in the mid-seventies, it is still in alignment with more recent reforms in science, claiming that if we truly value the development of knowledge, skills, and attitudes that are unique to practical work in science laboratories, appropriate assessment of these outcomes must be developed and implemented continuously by teachers in their own laboratory-classrooms. The *National Science Education Standards* (National Research Council, 1996), for example, indicate that all the student's learning experiences should be assessed and that the assessment should be authentic. Attention to such *standards*, however, has promoted testing that has generally not incorporated the assessment of performance and inquiry, although there have been a few noteworthy efforts to do so. Researchers, teachers, and testing jurisdictions, whose goal is to assess comprehensively the learning that takes place in school science generally, or in school laboratories more specifically, should use appropriate assessment tools and methodologies to identify what the students are learning (conceptual as well as procedural).

ASSESSING STUDENTS' PERFORMANCE, PROGRESS, AND ACHIEVEMENT USING DIFFERENT MODES OF PRESENTATIONS IN THE CHEMISTRY LABORATORY

Bryce and Robertson (1985), in their review of the literature regarding assessment in the laboratory, wrote that in many countries teachers spent considerable amounts of time in supervising laboratory work, but the bulk of science assessment is traditionally non-practical in nature. More recently, Yung (2001). on the basis of a study conducted in Hong Kong in the context of biology learning. presented data that demonstrate the complexity of assessment in school science laboratories. According to Yung, teachers should be aware of the potential of assessing their students regarding the improvement of teaching and learning. However, he claims that even as we enter the 21st century, teachers continue to assess their students using paper and pencil tests, thus neglecting many of the most important components of students' performance in the science laboratory in general, and the inquiry laboratories in particular.

In the previous section we presented the four phases that comprise practical work in the chemistry laboratory. Kempa (1986) suggested that these phases of experimental work provide a valid framework for the development and assessment of practical skills. In order to assess these phases, valid, reliable, and usable measures must be developed and implemented. A review of the literature (Ganiel & Hofstein, 1982; Bryce & Robertson, 1985; Giddings & Hofstein, 1990; Giddings, Hofstein, & Lunetta, 1991; Tamir, Doran, & Chye, 1992; Lazarowitz & Tamir, 1994; Lunetta, 1998; Hofstein, Kipnis, & Shore, 2004) has shown that in general, several distinct categories of assessment are available to assess some or all these phases: written evidence (either traditional laboratory reports or paper and pencil tests); one or more practical examinations; continuous assessment by the science teacher or researcher; and the combined methods in which at least two of the assessment methods are employed.

Written evidence

Traditionally, science teachers have been assessing their students' performance in the laboratory on the basis of their written reports, during or after the laboratory exercise. Unfortunately, this method of assessment provides only limited information regarding the students' behavior and performance during the practical exercise. The second form of written evidence is a paper and pencil test, designed to assess students' knowledge and understanding of the use of experimental techniques and the principles underlying laboratory work and procedures. Such a method was employed by Ben-Zvi, Hofstein, Samuel and Kempa (1976). The test was divided into two sections, dealing with (1) principles and techniques, and (2) methodology. In this case, too, the method is limited to the more theoretical components of the laboratory work and therefore does not provide evidence for the more performance-type activities.

Practical Examination(s)

This type of examination is the most valid approach for assessing the *performance* phase, in which the student is involved in the conducting of and decision making within the experimental and observational phases. Examples of practical examinations used in research studies were found mainly in studies conducted and published throughout the 1970s (e.g., Yager, Engen, & Snider, 1969; Tamir, 1972, 1974; Eglen & Kempa, 1974; Kempa & Ward, 1975).

Ben-Zvi, Hofstein, Samuel, and Kempa (1976) used three practical tests in a study in which the educational effectiveness of a filmed experiment was investigated in the context of high-school chemistry learning. Two groups of students were involved in the study: a group of students who watched the experiments performed in 8mm film-loops and a control group in which the participating students performed the same experiments as hands-on activities. The first practical test required students to perform experimental work according to well-defined instructions; its main purpose was to examine manipulative skills. This was done by using a checklist embracing four subcategories of manipulative skills (experimental techniques, procedures, manual dexterity, and orderliness) suggested previously by Eglen and Kempa (1974).

The second practical test was developed with the goal in mind of assessing students' skills in the context of a problem-solving situation involving not only the activities to be performed but also the planning of an experimental procedure in an area not previously encountered by the students, for example, a quantitative investigation of the effect of heat on a carbonate. The same checklist was used as in the first practical test.

The third practical mode of assessment was an *observational test.* This test consisted of six test-tube-type experiments covering the following perceptional areas: color change, change of temperature, evolution of gases, and the precipitation of solids. The results of the study indicated that, except for the manipulative skills area, filmed experiments presenting experimental situations are an effective substitute for students' individual laboratory work in that they do not adversely affect cognitive or laboratory-based problem-solving achievement. However, in the area of routine manipulative skills, direct experience with laboratory work obviously leads to a higher performance level; but the relative advantage gained by the experiment-group students over the film-group students is small and strongly supports the potential of filmed experiments as a means of teaching manipulative skills simply.

The main obstacle in using the *'practical examination'* approach is that its implementation is limited to those experiments that can be readily administered to students in a limited time, which obviously restricts both the scope and validity of the assessment. In addition, it can also have undesirable effects on the choice of experiments conducted throughout the year. In other words, in general, teachers limit their choice of experiment to those highly related to the type of experiment utilized in a practical test. There has been a change towards continuous internal assessment of practical abilities conducted and monitored by teachers in their school system in attempting to overcome these limitations and obstacles.

Continuous assessment

In attempting to overcome the drawbacks of practical examinations, teachers have shifted towards implementing the assessment of students' achievement and progress in the science laboratory by using continuous assessment. The philosophy behind this method is that students are not only evaluated at the end of the learning process, but instead this is a continuous and dynamic process (JMB, 1979). In this form of assessment the science teacher or researcher) unobtrusively observes each student during the normal laboratory session and rates him or her regarding specific preconceived criteria and marking schemes (JMB, 1979; Ganiel & Hofstein, 1982; Giddings & Hofstein, 1990; Hofstein, Kipnis, & Shore, 2004). This system was largely formalized in the United Kingdom (JMB, 1979) as an alternative to one-time practical examinations that were administered by the government. Continuous assessment of practical work on several occasions throughout the year(s) is necessary to adequately cover the variety of tasks and skills that comprise a total program of science-based practical work. The advantage of the continuous assessment of students' work in the laboratory is discussed in detail in a comparative study reported by Ganiel and Hofstein (1984).

The continuous assessment method was implemented in Israel in a study in which students perform inquiry-type experiments (Hofstein, Kipnis, & Shore, 2004). For this study, about 100 inquiry-type experiments were developed and implemented in 11th and 12th grade chemistry classes in Israel (for more details about the developmental procedure, assessment of students' achievement and progress, and the professional development of the chemistry teachers see Hofstein et al., 2004). Almost all the experiments were integrated into the framework of the key concepts taught in high-school chemistry, namely acids-bases, stoichiometry, oxidation-reduction, bonding, energy, chemical equilibrium, and the rates of reactions. These experiments have been implemented in the school chemistry laboratory in Israel for the last five years. As previous mentioned, under these conditions, we controlled such variables as the professional development of teachers, the continuous assessment of students' progress in terms of achievement in the laboratory, and the allocation of time and facilities (materials and equipment) for conducting inquiry-type experiments.

Typically in the chemistry laboratory the students perform the experiments in small groups (3-4), by following the instructions in the laboratory manual. Table 1 presents the various stages that each of the groups underwent in order to accomplish the inquiry task. In the first phase (the pre-inquiry phase), the students are asked to conduct the experiment based on specific instructions. This phase is largely 'close-ended', in which the students are asked to conduct the experiment based on specific instructions given in the laboratory manual. Thus, this phase provides the students with very limited inquiry-type experiences. The 'inquiry phase' (the second phase) is where the students are involved in more 'open-ended-type' experiences such as asking relevant questions, hypothesizing, choosing a question for further investigation, planning an experiment, conducting the experiment (including observations), and finally analyzing the findings and arriving at conclusions. It is thought that this phase allows the students to learn and experience science with greater understanding. Moreover, it provides them with the opportunity to construct their knowledge by actually doing scientific work. In addition, conducting such experiments provides the students with opportunities to practice metacognitive activities. Baird (1990) suggested that metacognitive skills are "learning outcomes associated with certain actions taken consciously by the learner during a specific learning episode" (p. 184). Metacognition involves elaboration and application of one's learning, which can result in enhanced understanding. In other words, students are provided with a learning situation in which they take control (and are aware) of their own learning in the search for understanding.

A recent study (Hofstein, Navon, Kipnis, & Mamlok-Naaman, in press) has clearly shown that chemistry students who were involved in such activities (inquiry) were able to ask more and better questions regarding chemical phenomena when compared to a group of students who were not involved in such experiences. In addition, it was found that students who were involved in inquiry-type activities developed the ability to also ask questions in non-experimental chemistry learning experiences such as reading scientific articles (primary articles written by chemists regarding their research). This again indicates that students who

TABLE 1: *Phases in inquiry-type experiment.*

Phase 1: Pre-inquiry	Abilities and skills
Describe in detail the apparatus in front of you.	
Add drops of water to the small test tube, until the powder is wet. Seal the test tubes immediately.	-Conducting an experiment.
Observe the test tube carefully and record all your observations in your notebook.	-Observing and recording observations.
Phase 2: The inquiry phase of the experiment	
1. Hypothesizing	
Ask relevant questions. Choose one question for further investigation.	-Asking questions and hypothesizing.
Formulate a hypothesis that is aligned with your chosen question.	
2. Planning an experiment	
• Plan an experiment to investigate the question.	-Planning an experiment.
• Present a plan to conduct an experiment.	
• Ask the teacher to provide you with equipment and material to conduct the experiment.	-Conducting the planned experiment.
• Conduct the experiment that you proposed.	
• Observe and note clearly your observations.	
• Discuss with your group whether your hypothesis was accepted or you have to reject it.	-Analyzing the results, asking further questions, and presenting the results in scientific way.

were exposed to inquiry laboratories developed high-level learning skills and metacognitive abilities.

Table 1 details the stages that students undergo in conducting a typical inquiry-type experiment, fondly called "*Experimenting with a couple of test tubes*". This experiment can be conducted as an introductory experiment in the context of learning the topic that deals with energy changes in chemical reactions (for more details about the experiment, see Table 1). Note that students receive no information regarding the compounds and the reaction that takes place, which ensures that they will focus on the task and will follow the various stages of the inquiry pathway.

Development and implementation of assessment tools

In order to assess students' achievement and progress during the performance of the experiments, we developed two assessment tools (Levy Nahum, 2000) that are used continuously by the chemistry teachers in their classroom laboratories. The development of the assessment tools included the identification of assessment criteria and the weight assigned to each criterion. This procedure was conducted by the trial chemistry teachers who participated in the intensive professional development workshop aimed at preparing them for the implementation of the inquiry experiments in their schools. For details about the weight assigned to each criterion, see Table 2.

TABLE 2: *Percentage weight for each criterion: (based on the "hot reports" and teacher's observations of the student's work).*

	Assessment based on the "hot reports" (80%)								Assessment based on the teacher's observation (20%)		
Criteria	Observation	Theoretical stages of the inquiry			Post-inquiry stage			Group report			
Percentage weight (%)	10	35			30			5	5	5	10
Experiment number	Recording	Questioning	Hypothesizing	Planning	Presentation of results	Conclusions	Summary	Written presentation	Manual dexterity	Cooperation in group	Communication skills
Average											

Note that such a table is prepared for each student for each experiment. The teacher can decide whether to assess all the experimental components or only part of them. This depends on the teacher's goals, curricular constraints, and the topic taught at that time.

All together, the assessment tools underwent four revisions. The changes made were based on the trial teachers' feedback from their respective schools and from the discussions and deliberations that were held during the professional development of the trial teachers (for more details on the trial teachers' professional development, see the next section). This procedure ensured that the assessment tools improved with regard to their validity and usability.

The second assessment tool developed for use in this study is based on the students' fondly called '*hot-reports*'. These, are reports produced by the groups of students who work on the inquiry activities; they are prepared in the laboratory during or immediately after the lab session. These reports provide a valid source of information about the students' observations, analysis of the data, questions asked, as well as suggested hypothesis and plans for further experimentation to find an answer to one or more of the questions posed by the group. The observations regarding the students' performance, together with the assessment of the '*hot-reports*' provide the chemistry teacher with valid and wide-ranging information about their students' achievement and progress in the laboratory. The *'hot-reports'* are collected in the students' portfolio. The main purpose of a portfolio is to collect, over a period of time, evidence regarding the performance, activities, and accomplishments of students. The evidence accumulated in the portfolio can then be used by the teachers in their classrooms and laboratories (or external examination authorities) to assess the students' achievement and progress. The sum of the results of the assessment of the '*hot reports*' and the teacher's direct observations, in about 20 experiments, during a period of two years, determines the students' grades in the laboratory. This grade counts for 20% of their total grade in chemistry.

STUDENTS' ATTITUDE TOWARDS AND INTEREST IN SCHOOL CHEMISTRY LABORATORY WORK

Developing favorable attitudes towards science has often been listed as one of the important goals of science teaching. Hofstein and Lunetta (1982, 2004) have suggested that the laboratory, as a unique social setting, has (when activities are organized effectively) great potential in enhancing social interactions that can contribute positively to developing attitudes and cognitive growth.

Several studies published in the 1970s and early 1980s (as reviewed by Bates, 1978, and by Hofstein & Lunetta, 1982) reported that students enjoy laboratory work in some courses and that laboratory experiences resulted in positive and improved student *attitudes* and *interest* in science. For example, Ben-Zvi, Hofstein, Samuel, and Kempa (1976b) reported on chemistry students who were asked to rate their perceptions of the relative effectiveness of instructional methods for promoting their interest in and attitude towards learning chemistry. They reported that personal involvement in the chemistry laboratory was the most effective instructional method for promoting their interest in chemistry studies when contrasted with teachers' demonstrations, filmed experiments, classroom discussions, and teacher's lectures. In the previous chapter, Ben-Zvi et al. (1976a) reported that in general, filmed experiments are effective substitutes to students' own experimentation, in regard to the cognitive, and to a considerable extent, the psychomotor outcomes resulting from them. It is clear from this study that that this does not apply to students' perceptions of the learning approaches and their liking for them.

In addition, in a study in which we explored the reasons for students' enrollment in more advanced (post-compulsory) courses in high-school chemistry, we found that one of the key reasons was their experiences with practical exercises in the chemistry laboratory (Milner, Hofstein, & Ben-Zvi, 1987). These results are in alignment with findings in the USA (Charen, 1966; Johnson, Ryan, & Schroeder, 1974) Also, more recently, in Nigeria, Okebukola (1986) summarized his study, claiming that a greater degree of participation in the science laboratory resulted in an improved attitude towards chemistry learning in general and towards learning in chemistry laboratory in particular. Okebukola (1986) used the *Attitude* *towards and interest in chemistry laboratory questionnaire* developed and validated by Hofstein, Ben-Zvi, and Samuel (1976) in Israel. This questionnaire was used in a study conducted in Israel (N=505, in 10-12th grades, in 5 schools).

Our analysis of students' responses using factor analytic investigation, revealed that students' attitude towards the chemistry laboratory is not one-dimensional, as it was assumed to be for attitudes towards science and school science (Hofstein, Ben-Zvi, Samuel, & Kempa, 1975). The following attitudinal dimensions were obtained: *learning in the science laboratory, the amount of laboratory work,* and *the value of laboratory work.* Importantly, it was found that the measure is sensitive to the type of the experiences to which the students are exposed, to differences in the type of subject that the students learn (biology, chemistry, and physics), and finally to gender differences. For example, it was found that chemistry students in 12th grade (age 17) found laboratory work less stimulating than their 11th and 10th grade counterparts. In addition, a comparison of boys and girls regarding the various attitudinal dimensions revealed no significant differences, unlike previous work in physics learning (Walberg, 1967), in which it was found that the boys' attitude is significantly more positive. This questionnaire was administered more recently in a study in which two groups of students were compared (Kipnis & Hofstein, 2003). The first group consisted of students who performed inquiry-type chemistry experiments (Hofstein, Kipnis, & Shore, 2004), whereas the other group comprised students whose laboratories mainly consisted of confirmatory-type experiments. It was found that in general, the students who were involved in the inquiry-type practical experiences developed a much more positive attitude towards learning chemistry in general and towards learning chemistry in a laboratory setting in particular compared to another group (control).

At the beginning of the 1990s, the focus of scholarly research in the science education literature moved away somewhat from the affective domain and moved more towards the cognitive domain in general and towards conceptual change in particular. Two comprehensive reviews that were published in the early 1990s (Hodson, 1993; Lazarowitz & Tamir, 1994) did not discuss research focused on affective variables such as attitudes and interest. Nevertheless, the science education literature continues to emphasize that laboratory work is an important medium for enhancing attitudes, stimulating interest and enjoyment, and motivating students to learn science in general and chemistry in particular (e.g., Freedman, 1997; Thompson & Soyibo, 2002).

STUDENTS' PERCEPTIONS OF THE SCHOOL SCIENCE LABORATORY LEARNING ENVIRONMENT

The science laboratory is a setting in which students work cooperatively in small groups to investigate phenomena, a unique mode of instruction, and a unique mode of learning environment. Hofstein and Lunette (1982) and Lazarowitz and Tamir (1994) suggested that laboratory activities have the potential to enhance constructive social relationships as well as positive attitudes and cognitive growth. Cooperative team effort is required for many laboratory activities. The less formal atmosphere (compared to the classroom), and opportunities for more constructive interactions between students and between students and their teachers have the potential to promote social interactions and thus create a positive learning environment (Tobin, 1990).

An important and valid source of information regarding the different types of interactions that occur in science laboratories can be obtained by using measures that assess students' perceptions of the laboratory learning environment. The need to assess the students' perceptions in the science laboratory was first approached seriously by a group of science educators in Australia (Fraser, McRobbie, & Giddings, 1993), who developed and validated the *Science Laboratory Environment Inventory* (SLEI). This instrument, consisting of eight learning environment dimensions (scales) (*cohesiveness, open-endedness, integration, rule-clarity, material environment, teacher-supportiveness, involvement,* and *organization)* was found to be sensitive to different approaches to laboratory work, e.g., high inquiry or low inquiry and in different science disciplines such as biology or chemistry laboratory learning environments (Hofstein, Cohen, & Lazarowitz, 1996; Fisher, Harrison, Henderson, & Hofstein, 1999).

The SLEI has been used in several studies conducted in different parts of the world. One comparative study examined students' perceptions in six countries: UK, Nigeria, Australia, Israel, USA, and Canada (Fraser & McRobbie, 1995). Fraser, McRobbie, & Giddings (1993) in Australia, found that students' perceptions of the laboratory learning environment accounted for significant amounts of the variance of the learning beyond that due to differences in their abilities.

During the academic year 2000-2001 we conducted a comparative study (Hofstein, Levi Nahum, & Shore, 2001), in which the perceptions of two groups of students regarding the classroom laboratory learning environment was assessed and statistically compared. The first group consisted of students who were involved in the inquiry laboratory (Hofstein, Kipnis, & Shore, 2004) and the second group (control) consisted of students who were involved in laboratory activities that are clear, 'close-ended', and directly related to the concepts taught at that time in the regular classroom (i.e. non-inquiry laboratory experiences). The two groups were compared using both a quantitative method (using the SLEI) and a qualitative method, namely structured interviews. Students were given two versions of the SLEI questionnaire, namely the *actual* version in which students were asked to present their perceptions regarding the existing learning environment and the *preferred* version in which they were asked to present their expected classroom learning environment.

Our analysis regarding the students' perceptions clearly demonstrated that students who were involved in inquiry-type investigation found the laboratory learning environment to be more *open-ended*, and more *integrated* with a conceptual framework than did students in a control group. Moreover, it was found that the gap between the *actual* and the *preferred* learning environment on the various scales was significantly smaller in the inquiry group than in the control group. Also, with regard to the actual and preferred learning environment in the chemistry laboratory, the most predominant and statistically significant differences were observed for the open-endedness and the involvement scales, with the inquiry group having much more favorable perceptions than the control group. We observed that students perceived that they were more involved in the learning process and found the procedures more open-ended. These findings are in alignment with recent trends to enhance the involvement of students in the learning process and in constructing their knowledge of scientific concepts and processes. A comparison of actual vs. preferred differences in a laboratory learning environment revealed that *integration* of the laboratory experiences with other pedagogical interventions and classroom instructional techniques was associated with a significant reduction in the magnitude of the differences. In other words, the inquiry group found the actual learning environment significantly more aligned with their preferred environment compared with the control group. The value of integration with the other experiences is well documented in the literature. In recent years there is a growing awareness that learning is contextualized and that learners construct knowledge by solving genuine and meaningful problems (Brown, Collins, & Duguid, 1989). Similar results regarding students' perceptions were obtained in the interviews conducted among a small sample of students.

In 1982 Hofstein & Lunetta wrote that:

"Because creating [a] healthy learning environment is an important goal for many contemporary educators, there is a need for more research that will assess how the time spent in laboratory work and how specific activities in the laboratory work and how specific activities in the laboratory affect [the] learning environment. It will be desirable to study further the effects of different modes of practical work (e.g. open-inquiry) on the learning environment. (p. 212*).*

Based on our study and on the literature, clearly, if students' positive perceptions of the science laboratory learning environment, i.e. cooperative learning, collaboration, and developing a community of inquiry are among the important intended outcomes of school laboratory experiences, then these outcomes should be assessed by teachers as a regular part of course evaluation. The *Science Laboratory Environment Inventory* could be used by teachers as one part of *action research* intended to examine the effects of a new laboratory teaching approach or strategy and as part of improving instruction.

SUMMARY: A LOOK AT THE FUTURE

In this paper I reviewed 30 years of experience with the various dimensions related to the chemistry laboratory. There is no doubt that throughout the years there has been substantial growth in understanding associated with teaching, learning, and assessment in the school chemistry laboratory work. Although much research has been conducted in order to investigate the educational effectiveness of the laboratory as a unique learning environment, we still strive to identify and show the relationship between experiences in the laboratory and students' learning. Furthermore, it is unreasonable to assert that the laboratory is an effective and efficient teaching medium for achieving all goals in chemistry education. However, based on the research literature and on this review, sufficient data do exist to suggest that laboratory instruction can play an important part in the achievement of some of these goals. Appropriate laboratory activities can be effective in promoting cognitive skills, metacognitive skills, practical skills, and attitude and interest towards chemistry, learning chemistry, and practical work in the context of chemistry learning. In addition, it is clear that providing students with authentic and practical learning experiences has the potential to vary the classroom learning environment and thus to enhance students motivation to study science (chemistry).

At the beginning of the 21st century we operate in an era in which *inquiry* has re-emerged as a central style advocated for science teaching and learning (NRC, 1996, p. 23):

Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations.

If used properly, the laboratory has the potential to be an important medium for introducing students to central conceptual and procedural knowledge and skills in science (Bybee, 2000). Krajcik, Mamlok, and Hug (2001) suggested that students who perform the various phases of inquiry are challenged by asking appropriate questions, finding and synthesizing information, monitoring scientific information, designing investigations, and drawing conclusions.

In recent years, there has been substantial growth in understanding associated with teaching, learning, and assessment in school science laboratory work. At the onset of the 21st century, when many are again seeking reform in science education, the knowledge that has been developed about learning based upon careful scholarship should be incorporated in that reform. The *"The less is more slogan"* in "*Benchmark for Science Literacy"* (AAAS, 1993, p.320) has guided curriculum development and teaching consistent with the contemporary reform. The intended message is that that formal teaching results in greater understanding when students study a limited number of topics, in depth and with care, rather than a large number of topics much more superficially, as is the case in many upper-secondary school science classrooms. Well-designed, inquiry-type laboratory activities can provide learning opportunities that help students develop high-level learning skills. They also provide important opportunities to help students learn to investigate (e.g. ask questions), to construct scientific assertions, and to justify those assertions in a classroom community of peer investigators in contact with a more expert scientific community. There is no doubt that such activities are time-consuming and, thus, the education system must provide time and opportunities for teachers to interact with their students and also time for students to perform and reflect on such and similar complex inquiry and investigative tasks. Such experiences should be integrated with other chemistry classroom learning experiences in order to enable the students to make connections between what is learned in the classroom and what is learned and investigated in the laboratory. This is largely based on the growing sense that learning is contextualized and that learners construct knowledge by solving genuine and meaningful problems (Brown, Collins, & Duguit, 1989). One of the most crucial problems regarding the implementation of inquiry-type laboratory experiments is the issue of assessing students' achievement and progress in such a unique learning environment. In general numerous science teachers are not using authentic and practical assessment on a regular basis. The *National Science Education Standards* (NRC, 1996) indicate that all the students' learning experiences should be assessed. As teachers, whose goal is to assess comprehensively what takes place in school science in general, or in the laboratory more specifically, we should use appropriate assessment tools and methodologies to identify what students are learning both in terms of concepts as well as procedures. The effect of such experiences on students' interest and motivation should also be assessed.

CONCLUDING REMARKS

In recent years, new information based on scholarly research has been gathered regarding the limitations and advantages of the chemistry laboratory. In addition, the following important reasons continue to be relevant:

- School laboratory activities have special potential as media for learning that can promote important science learning outcomes for students;
- Teachers need knowledge, skills, and resources that enable them to teach effectively in practical learning environments. They need to be able to enable students to interact *intellectually* as well as *physically*, involving hands-on investigation and minds-on reflection;
- Students' perceptions and behaviors in the science laboratory are greatly influenced by teachers' expectations and assessment practices and by the orientation of the associated laboratory guide, worksheets, and electronic media;
- Teachers need ways to find out what their students are thinking and learning in the science laboratory and classroom.

In 1980 Pickering wrote an essay titled: *Are lab courses a waste of time?* He wrote:

> *The job of lab courses is to provide the experience of doing science. While the potential is rarely achieved, the obstacles are organizational and not inherent in laboratory teaching itself. That is fortunate because reform is possible and reform is cheap. Massive amounts of money are not required to improve most programs; what needed is more careful planning and precise thinking about educational objectives. By offering a genuine, unvarnished scientific experience, a lab course can make a student into a better observer, a more careful and precise thinker, and a more deliberative problem solver. And that is what education is all about.*

Although this essay was written 25 years ago, I sincerely believe that it is valid and relevant to date.

ACKNOWLEDGMENT: Much of the research that is described in this review was inspired by my work over a period of 30 years with colleagues in the UK, USA, Australia, and in Israel. My work on practical work (including my doctoral study) was highly influenced through support and advice obtained from and collaboration with Prof. *Richard Kempa*, from the University of Keele, Staffordshire, UK. In the USA, my collaboration with Prof. *Vincent Lunetta*, from Pennsylvania State University, helped me in broadening the scope of practical work and in developing a critical point of view regarding its educational effectiveness. Also very helpful were Professors *Geof Giddings*, *Darell Fisher*, and *Barry Frazer*, from Curtin University, Australia, who introduced to me the SLEI, and finally friends, colleagues, and students; Dr. *Ruth Ben-Zvi, Relly Shore, Tami Levy Nahum*, and *Mira Kipnis*) at the Department of Science Teaching, The Weizmann Institute of Science in Israel, who throughout the years, helped me and collaborated with me on many of these research studies.

CORRESPONDENCE: *Avi HOFSTEIN, Department of Science Teaching, The Weizmann Institute of Science, Rehovot 76100, Israel; fax: 972-8-9344115*; *e-mail: avi.hofstein@weizmann.ac.il*

Avi Hofstein holds a B.Sc. in chemistry, an M.A in education, and a Ph.D. in science education (chemistry) from *The Weizmann Institute of Science*. For more than 15 years he taught chemistry in two high schools in Israel. Currently, he is the head of the “Chemistry Group” and head of the “Science for All” programs in the Department of Science Teaching, The Weizmann Institute of Science, Israel. For more than 30 years, he has been involved in all the facets of the curricular process in chemistry, namely development, implementation, evaluation, and research. In regard to general science education, he has conducted research in the following areas: the science (chemistry) laboratory, classroom, outdoors, and laboratory learning environments, learning difficulties and students' misconceptions in chemistry, and attitudinal and motivational studies. In recent years, he is involved in the development of leadership amongst chemistry teachers to promote reform in the way chemistry is taught in Israel.

REFERENCES

American Association for the Advancement of Science (AAAS) (1993). *Benchmarks for scientific literacy*. New York: Oxford University Press.

Baird, J.R. (1990). Metacognition, purposeful inquiry, and conceptual change. In E. Hegarty-Hazel (ed.)., *The student laboratory and the science curriculum.* London: Rutledge.

Bates, G.R. (1978). The role of the laboratory in secondary school science programs. In M.B. Rowe, (ed.). *What research says to the science teacher*, Vol. 1. Washington D.C: National Science Teachers Association.

Ben-Zvi, R., Hofstein, A., Samuel, D., & Kempa, R. F. (1976a). The educational effectiveness of filmed experiments in high school chemical education. *Journal of Chemical Education, 53*, 581-520.

Ben-Zvi, R., Hofstein, A., Samuel, D., & Kempa., R. F. (1976b). The attitude of high school students to the use of filmed experiments. *Journal of Chemical Education, 53*, 575-577.

Ben-Zvi, R., Hofstein, A., Samuel, D., & Kempa, R. F. (1977). Modes of instruction in high school chemistry. *Journal of Research in Science Teaching, 14*, 433-439.

Blosser, P. (1980). *A critical review of the role of the laboratory in science teaching*. Columbus OH: Center for Science and Mathematics Education.

Brown, J.S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18,* 32-41.

Bryce, T.G.K. & Robertson, I.J. (1985). What can they do? A review of practical assessment in science. *Studies in Science Education, 12,* 1-24.

Bybee, R. (2000). Teaching science as inquiry, In J. Minstrel, & E. H. Van Zee (eds.). *Inquiring into inquiry learning and teaching in science*, pp. 20-46. Wasington DC: American Association for the Advancement of Science (AAAS).

Charen, G. (1966). Laboratory method build attitudes*, Science Education, 50*, 54-57.

Eglen, J.R., & Kempa, R.F. (1974). Assessing manipulative skills in practical chemistry. *School Science Review, 56*, 737-740.

Fisher, D., Harrison, A., Henderson, D., & Hofstein, A. (1999). Laboratory learning environments and practical tasks in senior secondary science classes. *Research in Science Education, 28*, 353-363.

Fraser, B. & McRobbie, C.J. (1995). Science laboratory classroom environments at schools and universities: A cross-national study. *Educational Research and Evaluation, 1*, 289-317.

Fraser, B., McRobbie, C.J., & Giddings, G.J. (1993). Development and cross-national validation of a laboratory classroom instrument for senior high school students. *Science Education, 77*, 1-24.

Feedman, M. P. (1997). Relationship among laboratory instruction, attitude towards science and achievement in science knowledge. *Journal of Research in Science Teaching, 34*, 343-357.

Ganiel, U. & Hofstein, A. (1982). Objective and continues assessment of student performance in the physics laboratory. *Science Education, 66*, 581-591.

Garnett, P.J., Garnett, P.J., & Hackling, M. W. (1995). Refocusing the chemistry lab: A case for laboratory-based investigations. *Australian Science Teacher Journal, 41*, 26-32.

Giddings, G. J. & Hofstein, A. (1980). Trends in the assessment of laboratory performance in high school science instruction. *The Australian Science Teacher Journal, 26*, 57-64.

Giddings, G.J., Hofstein, A., & Lunetta, V.N. (1991). Assessment and evaluation in the science laboratory. In Woolnough, B.E. (ed.)., *Practical science*, pp. 167-178. Milton Keynes: Open University Press.

Gunstone, R.F. (1991). Reconstructing theory from practical experience. In Woolnough, B.E. (ed.), *Practical science*, pp. 67-77. Milton Keynes: Open University Press.

Gutman, H. F. (1940). The life of Ira Ramsen. *Journal of Chemical Education*, 17.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education, 22*, 85-142.

Hofstein, A. (1988). Practical work in science education II. . In P. Fensham (ed.), *Developments and dilemmas in science education*, pp 189-217. London: Falmer Press.

Hofstein, A., Ben-Zvi, R., & Samuel, D. (1976). The measurement of interest in and attitude to laboratory work amongst Israeli high school students. *Science Education, 60*, 401-411.

Hofstein, A., Cohen, I., & Lazarowitz, R. (1996). The learning environment of high school students in chemistry and biology laboratories. *Research in Science and Technological Education, 14*, 103-115.

Hofstein, A. & Kempa, R. F. (1985). Motivating aspects in science education: An attempt at an analysis. *European Journal of Science Education, 7*, 221-229.

Hofstein, A., Levi-Nahum, T., & Shore, R. (2001). Assessment of the learning environment of inquiry-type laboratories in high school chemistry. *Learning Environments Research, 4*, 193-207.

Hofstein, A. & Lunetta,V.N. (1982). The role of the laboratory in science teaching: Neglected aspects of research. *Review of Educational Research, 52*, 201-217.

Hofstein, A. & Lunetta, V, N. (2004). The laboratory in science education: Foundation for the 21st century. *Science Education, 88*, 28-54.

Hofstein, A., Navon, O., Kipnis, M., & Naaman-Mamlok, R. Developing students' ability to ask more and better questions resulting from inquiry-type chemistry laboratories. *Journal of Research in Science Teaching (in press).*

Hofstein, A., Shore, R., & Kipnis, M. (2004). Providing high school chemistry students with opportunities to develop learning skills in an inquiry-type laboratory - A case study. *International Journal of Science Education 26*, 47-62.

Johnson, R.T., Ryan, F. L., & Schroeder, H. (1974). Inquiry and the development of positive attitudes. *Science Education, 58*, 51-56.

Joint Matriculation Board (JMB) (1979). *The internal assessment of practical skills in chemistry: Suggestion for practical work and advice on sources of information*. Universities of Manchester, Liverpool, Leeds, Sheffield, and Birgmingham.

Kelly, P. J. & Lister, R. E. (1969). Assessing practical ability in nuffielda-level biology. In J. F. E. Eggleston & J. F. Kerr (eds.), *Studies in assessment*. London: English Universities Press.

Kempa, R. F. (1986). Assessment in science, Cambridge: Cambridge Science Education Series, Cambridge University

Kempa, R. F. & Ward, J.F. (1975). The effect of different modes of task orientation on observations attained in practical chemistry. *Journal of Research in Science Teaching. 12*, 69-76.

Kipnis, M., & Hofstein, A. (2003). The attitude towards laboratory work: A comparison of inquiry-type with more conventional approach (An internal report). The Department of Science Teaching, The Weizmann Institute of Science (in Hebrew).

Krajcik, J., Mamlok, R., & Hug, B. (2001). Modern content and the enterprise of science: Science education in the twentieth century. In L, Corno. (ed.), *Education across a century: The centennial volume*, pp. 205-238. NSSE: 100th Yearbook of the National Society for the Study of Education. Chicago: University of Chicago Press.

Lazarowitz, R. & Tamir, P. (1994). Research on using laboratory instruction in science, in D. L. Gabel (ed.), *Handbook of research on science teaching and learning*, pp. 94-130. New- York: Macmillan.

Levy Nahum, T. (2000). The assessment of inquiry-type laboratories (MSc Thesis). The Department of Science Teaching, The Weizmann. Institute of Science, Rehovot, Israel (in Hebrew).

Lunetta, V.N. (1998). The school science laboratory: Historical perspectives and context for contemporary teaching. In B. Fraser and K. Tobin (eds.), *International handbook of science education,* pp. 349-264. Dordrecht: Kluwer Academic Publishers.

Lunetta, V. N., Hofstein, A., & Giddings, G. G. (1981). Evaluating science laboratory skills. *The Science Teacher, 48*, 22-24.

Merrill, R.J. & Ridgway, D.W. *The CHEMStudy Story*. Freeman: San Francisco, 1969.

Milner, N., Ben-Zvi, R., & Hofstein. A. (1987). Variables that affect students enrollment in science courses. *Research in Science and Technological Education, 5*, 201-208.

National Research Council (2000). *Inquiry and the national science education standards*. Washington DC: National Academy Press.

Okebukola, P. A. O. (1986). An investigation of some factors affecting students' attitudes toward laboratory chemistry. *Journal of Chemical Education, 86*, 531-532.

Pickering, M. (1980). Are lab courses a waste of time? *The Chronicle of Higher Education, 19*, 80.

Ramsey, G. A., & Howe, R. W. (1969). An analysis of research on instructional procedures in secondary school science. *The Science Teacher, 36*, 72-81.

Tamir, P. (1972). The practical mode a distinct mode of performance. *Journal of Biological Education, 6*, 175-182.

Tamir, P., Doran, R, L., & Chye, Y, O. (1992). Practical skills testing in science. *Studies in Educational Evaluation, 18*, 263-275.

Thompson, J. & Soyibo, K. (2001). Effect of lecture, teacher demonstrations, discussion and practical work on 10th grader's attitude to chemistry and understanding of electrolysis. *Research in Science and Technological Education, 20, 25-37.*

Tobin, K.G. (1990). Research on science laboratory activities: In pursuit of better questions and answers to improve learning. *School Science and Mathematics, 90*, 403-418.

Walberg, H, J. (1967). Dimensions of scientific interest in boys and girls studying physics, Science Education, 51, 111-116.

Yager, R, E., Engen, J. B., & Snider, C. F. (1969). Effects of the laboratory and demonstration method upon the outcomes of instruction in secondary biology. Journal of Research in Science Teaching, 5, 76-86.

Yeany, K. H., Larusa, A. A., & Hale, M. L. (1989). A comparison of performance- based versus paper and pencil measures of science process and reasoning skills as influences by gender and reading ability. Paper presented at the annual meeting of the *National Association for Research in Science Teaching* (NARST). San Francisco.

Yung, B. H. W. (2001). Three views of fairness in a school-based assessment scheme of practical work in biology. *International Journal of Science Education, 23*, 985-1005.