Successful Strategies for Integrating High School Students into a Graduate Research Group

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Abstract: A series of pedagogical approaches are presented that have proven effective in integrating seven high school students over a period of six years into an active graduate research program. Students working independently on their own research projects have successfully explored a wide range of topics including hemoproteins, bioconjugation chemistry, drug delivery, perfusion chromatography, cyclic voltammetry, electronic absorption spectroscopy, and resonance Raman spectroscopy. Their original research contributions have been presented at regional and national American Chemical Society conferences and have been published as peer-reviewed technical papers. All student participants to date have been graduated from high school and have matriculated on scholarship at area colleges and universities where they continue to be successful academically and where the majority has selected science-related majors.

Introduction

Since the summer of 1994, seven high school students have participated as full members of my graduate research group at Northeastern University in Boston, MA (see Table 1). These students' strong work ethic, enthusiasm, and fearlessness have resulted in one invited oral presentation, four poster presentations at regional and national American Chemical Society meetings, and four papers [1–3] to date. My experiences working with these students have convinced me that summer research experience at area colleges and universities may be pivotal educational experiences increasing the likelihood that these students will consider science-related majors in college. For this reason, I was surprised to find that little information exists in the chemical education literature regarding effective pedagogical practices that may be used to successfully involve students in the research enterprise [4–5]. This is particularly surprising given the current level of interest across the country in institutionalizing undergraduate research on college and university campuses. Certainly, communicating effective strategies that facilitate effective learning of chemistry from research experiences represents a logical first step in identifying and developing useful models of successful research experiences that will have widespread pedagogical utility and impact. I, therefore, wish to present several approaches that have been highly effective in our ongoing efforts to successfully integrate high school students into an active graduate research program. Because the same approach has been used to involve over twenty undergraduates in undergraduate research over the past ten years, I believe these practices should also have widespread utility and value in the development of effective undergraduate research programs.

Challenges for the Faculty Mentor

In large part the practices that will be described in this article have evolved in response to specific challenges I have encountered in working with high school students. In particular, high school students usually have an unrealistic idea of what research is and how research is done; thus, the greatest challenge involves teaching them the pace at which scientific research is conducted. Most high school laboratory experiences mislead students to expect that research is all about activities such as mixing solutions together, making measurements, or performing calculations. These unfortunate experiences leave highly impressionable young students with an unrealistic sense of the time and effort that is required to plan and execute a successful experiment. Thus, the purpose of several of the practices described here is to help students discover what research is all about and to develop a realistic view of how to design and carry out a series of experiments in order to answer an interesting and meaningful scientific question.

Communication skills represent another significant challenge. All of my students to date have learned English as a second language. While they have had superior mathematical skills, I have observed that my students' communication skills (reading, writing, and public speaking) need improvement. Therefore, because both writing and public speaking are essential skills for a successful career in science today, I have made writing and speaking opportunities integral to my high school students' summer research experiences.

A final consideration in developing an effective approach to mentoring high school students has been the desire to provide adequate personal attention to each student's needs while not neglecting the training of graduate and postdoctoral students. For this reason, the number of students has been limited to, at most, two at any one time. Although working with one student is highly advantageous in terms of time, I have found that high school students are generally much happier working in a laboratory with another high school student present even if the other student is working on a different project; therefore, whenever possible, I prefer to support two students in my laboratory: a new ("rookie") student and a returning ("veteran") student—preferably a newly graduated high school senior. This situation is advantageous in that the veteran student can easily share from his or her rich research experience and provide peer advice on college-admissions-related issues.

Table 1. High School Students in Mabrouk's Laboratory

Student	Years in Mabrouk's lab	High school	Current college or university	Current year	Self-identified academic major
Kwai Dzy Mak	1994, 1995	Charlestown High	Northeastern University	senior	pharmacy
Jing Nuan Liu	1995	Charlestown High	Simmons College	junior	mathematics and economics
Li Ci Liang	1996	Charlestown High	Northeastern University	junior	business administration
Xing Qi Zhou	1996	Charlestown High	Withdrawn	junior	undecided
Qiu Ci Li	1997, 1998	West Roxbury High	Regis College	sophomore	biochemistry
Zhi Chen	1998, 1999	Charlestown High	U. Mass Amherst	freshman	chemistry
Xiang Rong Mei	1999	Charlestown High	NA	senior	NA

Table 2. Past Summer Research Projects for High School Students

Year	Title of research project	Instrumentation used	Techniques learned
1994, 1996	Preparation and Characterization of Microperoxidase Polyethylene Glycol	Perkin Elmer Lambda 9 UV-vis spectrophotometer, Waters HPLC	dialysis, ultrafiltration, open-column cation exchange chromatography, size exclusion HPLC, dilution, enzyme assay, pH measurement
1995	Measurement and Control of the pH of Benzene	pH meter, Perkin Elmer Lambda 9 UV-vis spectrophotometer	pH measurement, extraction, emulsion
1997, 1998	Preparation and Characterization of N-Acetyl-Microperoxidase-8	HP 8452A diode array UV-vis, PerSeptive Biocad Sprint HPLC, BAS 100B electrochemical workstation, homebuilt Raman spectrometer	ultrafiltration, dilution, cation exchange chromatography, cyclic voltammetry, pH measurement, electronic absorption spectroscopy, resonance Raman spectroscopy
1998, 1999	Isolation and Purification of Soybean Peroxidase	HP 8452A diode array UV-vis, PerSeptive Biocad Sprint HPLC	ultrafiltration, cation exchange chromatography, enzyme assay
1999	Spectroelectrochemical Study of Cyt c in Glycerol	HP 8452A diode array UV-vis, pH meter, BAS 100B electrochemical workstation	pH measurement, cyclic voltammetry, electronic absorption spectroscopy

Key Programmatic Aspects

Several activities have proven particularly useful in structuring an effective experience for all involved. These include a carefully crafted research project, the use of one-on-one mini-lectures, the use of standard operating procedures (SOPs) for all major pieces of instrumentation in the laboratory, full participation in weekly research group meetings, and the provision of opportunities for presentation and publication of resulting student work. Each of these aspects will be considered sequentially in the sections that follow.

1. Project Design. The first step is to define a good project. With young students careful project design has been shown to be very important. Doris Kimbrough [4] studied 9th and 10th grade participants in the NSF Young Scholars Program, a summer science program for precollege students and found that project design strongly influenced students' perception of the success of their individual research projects. In particular, she found that six characteristics play an important role in student perceptions: (1) how the project is structured, (2) the relevance of the project to student interests, (3) project flexibility, (4) the completeness of the project background, (5) the ability to obtain tangible results, and (6) the extent to which students are introduced to the project at the start of their research experience.

I have found that careful attention to each of these characteristics is indeed important in ensuring the success of a high school student's summer research project. Certainly, these characteristics are common sense: Everyone, high school students, undergraduates, graduate students, and postdoctoral students, appreciates being handed a well-designed, articulated, and doable project. The project should be interesting and relevant to the student and appropriate for the length of the student's stay in the laboratory, typically ten weeks in summer, but one which has meat and can grow with the student if he or she desires to return to the laboratory for a second summer. Indeed, everyone appreciates knowing that the research problem they are investigating will impact and benefit their world. In terms of specific types of problems, students tend to be naturally interested in problems relating to health and the environment. Some of the projects we have investigated in my laboratory are summarized in Table 2. Past projects have included (1) the preparation and physicochemical characterization of heme protein bioconjugates useful in drug delivery and in the field of nonaqueous enzymology, (2) investigating methods for measuring and controlling pH in water-immiscible solvents, and (3) isolating and purifying by HPLC a new peroxidase derived from soybean hulls. The last project in the above list is a particularly good example of an attractive and successful project. The student developed and published an HPLC method for purifying commercial soybean peroxidase last summer [3a]. This summer, the student, now confident and experienced in HPLC methods development, purchased chinese "Montsew" soybeans from a Boston Chinatown grocery, then isolated and purified the peroxidase. Her work has now provided my laboratory with the ability to isolate and purify our own enzyme very inexpensively in-house producing enzyme more catalytically active than that currently commercially available [3].

Table 3. Working Roadmap for the 1997 Summer Project "Preparation and Characterization of N-Acetyl Microperoxidase-8"

Step number	Task	Methodology	Concepts taught
1	acetylate microperoxidase-8	ultrafiltration, dialysis, pH meter	weighing, stoichiometry, acid-base, buffers, pH, ultrafiltration, dialysis
2	Prove peptide is acetylated (color test).	ninhydrin reaction	amino acids, peptides
3	Purify product by HPLC.	perfusion ion exchange HPLC	chromatography, ion exchange, HPLC, revisit buffers and pH, chromophore, UV-vis, absorbance
4	Demonstrate product purity.	electrospray mass spectrometry	ionization, mass spectrometry, electrospray
5	Characterize electronic structure of product.	UV–vis	coordination number, spin state, charge, revisit chromophore, absorbance, and UV-vis
6	Characterize product electrochemically in aqueous solution.	cyclic voltammetry	statistics, mass transport, redox, reversibility
7	Characterize product electrochemically in dimethyl sulfoxide.	cyclic voltammetry	revisit statistics, mass transport, redox, reversibility

Scheme 1. Summer 1995 Mini-Lecture Topics

- pH
- Strong acids and bases
- Weak acids and bases
- Buffers
- Dilution
- Emulsions
- pH meter
- Basic statistics (accuracy, precision, regression)
- Pegylation (biomolecular modification with poly(ethylene glycol)
- Chromatography
- Size exclusion chromatography
- Transmittance, absorbance, and color
- Beer's law and chromophores
- Electronic absorption spectroscopy

2. The Working Roadmap. In describing the technical approach to investigating student research problems, I have found a particularly useful approach involves the use of what I call the *working roadmap*. Each project is presented as a road map, a series of clear, bite-size objectives that represent doable tasks. The student and myself design the roadmap over the course of the summer. This is an important point because most students expect to be handed a detailed predesigned road map. This clarification helps move the student from the traditional classroom role as passive learner to the new and unfamiliar role as active learner and valued colleague. As we investigate our research problem together as a team, I emphasize the project as consisting of a series of bite-size tasks, obtainable objectives, and experimental skills. An example of a real working roadmap is shown in Table 3. By breaking the project into bite-size tasks, the students can measure their growth and progress over the course of the summer. This approach helps students see that they are making real progress toward the solution of their research problem.

3. Mini-Lectures. Before students begin work on a new task or learn a new skill, I usually give them a 15–30-min-long mini-lecture. The purpose of the mini-lecture is to teach the student some of the underlying fundamental concepts involved in their task and provide them with specific directions to accomplish the task. A representative list of mini-lectures for one student's project is shown in Scheme 1. I usually write everything we discuss on paper as I teach each concept. These sheets are given to the student at the end of each mini-lecture so that they have something permanent to refer to later in reviewing the new material. Although this approach is admittedly somewhat time-consuming, most students at this stage are more comfortable learning in a lecture format than they are learning independently by reading the primary technical literature, which admittedly assumes fairly rigorous advanced technical training. Because I ultimately want my students to teach themselves new concepts, skills, etc. over the course of the summer I use the mini-lectures to equip the students with the skills needed to access, search, and read the primary literature. As my students develop facility with their new skills, they are encouraged to read the primary literature on their own and to discuss their questions with my postdoctoral students, graduate students, and myself.

Following the mini-lecture, students are asked to apply the new concept to their own projects, usually on a model compound as mentioned above. In their first efforts, the student and I usually work side-by-side to ensure that a suitable level of proficiency is developed. When the student appears comfortable working on their own, I step aside and let the student work independently with the understanding that they approach me if they have any questions or need any help. The study of a model system coupled with personal coaching provides a built-in feedback mechanism and allows me to identify and correct early on any problems with communication, understanding, or laboratory technique so students do not lose self-confidence and momentum. I have found that the use of this approach helps to develop a sound macroscopic, then particulate, and finally a valid symbolic conceptual understanding of the underlying chemical phenomena. The process also allows me to frequently assess the student's understanding and to intervene when necessary. This minimizes the likelihood that students will construct and build on fundamental chemical misconceptions [6]. When students demonstrate success with the new skill by obtaining certain qualitative or quantitative results independently, the students perform the skill in their own specific project. For example, before performing modern HPLC to purify a new biomolecule, students first learn the basics of ion exchange chromatography for the open column ion exchange purification of cytochrome c, a task that usually requires one eight-hour day. Then the students transition to HPLC and separate a standard cation or anion exchange protein standard mixture in order to learn how to use the HPLC instrument in our laboratory (about one eight-hour day). At this stage, the students are usually relatively confident and independent and ready to tackle purifying their biomolecules by HPLC.

Students generally like this approach because the qualitative and quantitative results can be anticipated in advance based on the primary literature; therefore, they can assess the quality of the results for themselves. The approach fosters true student ownership and produces a healthy self-confidence that enables students to be active, thoughtful architects of their own projects. Several of my students have cited their favorite memory about their summer research experience as being the excitement they felt after getting the result *they* predicted.

The nature of the specific research problem and my students' own curiosity drive our summer curriculum and allow me to connect chemistry and chemical concepts to real-life situations. The use of mini-lectures also allows me to explicitly connect fundamental concepts to a real-world context. In the course of working on a project, we often visit and revisit a concept, such as acid–base chemistry, several times and in several different contexts, each time increasing the depth of our discourse. The mini-lectures are a wonderful mechanism for demonstrating to students, through their summer research projects, the interconnectedness of learning.

4. Standard Operating Procedures (SOPs). Another important element of my pedagogical approach to the research laboratory involves the use of standard operating procedures (SOPs) that describe the procedures for the standard methods and instruments that we use. SOPs are frequently used in industrial analytical laboratories as a means of controlling quality. SOPs perform the same function in our laboratory as well—they ensure that everyone in the laboratory produces high-quality results reproducibly because everyone is following the same set of written procedures. Each SOP is designed and written for a particular technique or instrument by the first high school student, undergraduate, or graduate student to use and master that specific technique or instrument. Because my laboratory is experimentally and instrumentally driven, we are constantly purchasing new instrumentation and investigating new experimental techniques; thus, there is always an opportunity to author or amend a SOP. In addition, because the SOPs are all written by past or present group members, this gives each student in the group confidence knowing that a peer wrote the SOP and that, therefore, they, too, can learn to operate this new instrument. Supporting Material (510043pms1.pdf) provides an example of a SOP authored by an NSF RAMHSS student.

5. Group Meetings. Another key element that has proven particularly effective in challenging my high school charges to grow as young scientists is our weekly research group meeting. Students frequently comment on how much they enjoy these get-togethers and how much they learn.

> "The [thing] I most liked to do during the summer was every Friday morning's group meeting. This meeting gave me a very good chance to communicate with other students in the laboratory. I had a sense of what they were doing and their progress. Besides I can exchange ideas and learn new things."

In our meetings, which usually last between one and two hours, we have explored together a number of different topics, including the format of a journal article, how to make effective poster presentations, the basics of chromatography, and bioinorganic chemistry. Several times, our research group has learned about new subjects by reading a book together, tackling a new chapter each week [7, 8]. One part of our weekly meeting is usually devoted to what some often call a Journal Club. Each student selects several journals from a list of the major journals, which I provide. The student is then responsible for copying and distributing the abstract of any papers relevant to any group member's research project. This activity encourages my students to discuss their work with each other. This aspect is particularly important because most of the projects in my laboratory are inter-related. The success of any one project is, therefore, necessarily tied to effective, open communication between all researchers. In addition, each student is asked to select, read, and summarize an interesting technical paper relevant to his or her own research efforts from their journals list. Each student prepares a short (one-page) written and oral (10-min) presentation with the purpose of sharing with the group what they have learned. Finally, students are scheduled to briefly (10 min) report to the entire group concerning their weekly accomplishments. This practice has several benefits. First, it provides students with a strong sense of personal ownership of their research problem. Secondly, it encourages students to develop a more global perspective regarding what the group as a whole is seeking to accomplish. Finally, it helps students to gauge their own individual progress in comparison to that of their peers within the group. This is extremely important because it helps each student have a more healthy perspective regarding his or her own progress and accomplishments.

Because of the difficulties speaking often presents for high school students and because students at this age tend to be somewhat shy, making oral presentations, even in the relatively informal group-meeting environment, can be difficult. I have encouraged my students to prepare their group-meeting and professional-meeting presentations in advance in writing so that I can review their work and help them to hone their writing skills. The reports also provide my students with an opportunity to put their thoughts and ideas into words on paper that they then have available to use in making their oral presentations at group meeting.

6. Professional Presentation of Research Findings. A final aspect that is critical to a student's perception of a successful research experience is the provision for professional presentations, such as poster presentations at regional or national conferences or the opportunity to co-author a technical paper. As mentioned at the beginning of this article, one invited oral paper, four poster presentations, and four technical papers have resulted from my students' work to date. These opportunities have been invaluable to my students' growth, enabling them to find out for themselves how good their work is and how knowledgeable they are. Certainly, not every student has been ready to make their professional debut in a public setting. Thus, I require each student to prepare a typewritten technical report at the end of the summer. Reference 3b represents a good example of a final report written by a student whose work had already resulted in one publication [3a]. For students such as this one who have completed a significant body of work that is suitable for presentation as a poster or eventual publication, the preparation of a poster or assembly of the rough draft of a paper is encouraged.

The requirement of a final report is mutually beneficial. First, the writing exercise forces each student to sit down at the end of the project, evaluate what they have accomplished, and articulate their accomplishments in writing. The students are usually amazed by how much they have learned. The final report also provides the students with something concrete that they can submit as part of their supporting college application materials, evidence of their abilities and their potential. At the same time, the report provides me, the faculty mentor, with a written record of the student's accomplishments that can be provided to the upper administration of the university to secure future institutional support and that can be used in the preparation of technical papers and presentations if the results are publishable.

Assessment

Evaluation of the effectiveness of my current pedagogical practices have thus far been limited to post-experience assessment. At the end of each summer, student participants are asked to complete written surveys that are used to evaluate the quality of their experiences (facts and skills learned) and to determine the level of their satisfaction. Other measures that I have used to assess the quality of my experiences are my students' success afterward in college and, in particular, whether they have chosen to pursue a science-related major—the majority have selected science-related majors including chemistry, biochemistry, pharmacy, and mathematics (see Table 1). Finally, student productivity, as measured by traditional research outcomes, specifically, poster presentations, oral papers, and published peer-reviewed technical papers have also been important considerations.

The benefits of these summer research opportunities for high school students have been many. First, on one level, summer research experiences have provided these students a paid summer job ($1,750–$2,000) and, therefore, work experience, which is advantageous for college admission applications. Secondly, and more importantly, these experiences provided my students with an opportunity to experience college and college life firsthand. High school students are often conflicted about whether they can realistically attend college due to financial concerns and the complexity of their families' lives. Third, my students have benefited by developing self-confidence, poise, and positive self-esteem through their interactions with undergraduates and graduate students in the research group, who have served as positive role models for the younger students. From a pedagogical standpoint, I have found that research experience transforms student attitudes toward chemical knowledge. Students begin to perceive that chemical knowledge is dynamic—that the body of scientific knowledge is not static but is constantly expanding and being refined. Perhaps most importantly, actual participation in the scientific enterprise has enabled my students to realistically visualize themselves as part of the greater scientific community and, therefore, has provided them with a new vision of themselves as leaders and future contributors to society and the world. Two of my students expressed it this way:

> "The whole summer means to me learning, growth, and experimenting although the material in the lab was hard for me as a high school student. Overall, I learned more than I had expected and meanwhile I discovered my interest and my love for a college life. Thanks SEED for giving me this chance. I feel SEED helped me not only in chemistry but also in the beginning of my college life. The most valuable thing to me was I realized my survival capability if I go to college. Before the SEED program, I was [lacking in] personal confidence to go to college under the pressure of competition with all the other American students. But SEED opened the road for me. I liked college life and I was sure I wanted to be part of it. Now, here I am, [having] passed my freshman year with an honors grade!"

> "Yes, I feel strongly that SEED helped me. It led me to the door of science and gave me the opportunity to explore science. The most valuable thing that I learned is not to give up when experiments failed. I have learned so much that surprised me. I learned how to set up and run experiments, how to write scientific papers, and how to communicate with other scientists (e.g., poster presentation in conference). The experiences I gained from the SEED program built up my confidence in scientific study, which helped me a lot in my chosen field, pharmacy study."

Equally important to consider have been the advantages for me as a faculty member in opening my laboratories to high school students. The presence of younger students has enriched the quality of the graduate research experience in many ways. Older students, who may be undergraduate, graduate, or postdoctoral students, have benefited from interacting with their high school apprentices by learning important managerial skills. The earnest, probing questions of the younger students has sharpened the technical knowledge of my graduate and postdoctoral students and has significantly improved the effectiveness of their communication skills. High school students have supercharged the laboratory with their enthusiasm and intense energy level. They possess a refreshing belief that they can quite literally accomplish anything and everything. This can be quite contagious and has sparked even the most jaded undergraduate and graduate students to give their very best. Finally, the efforts of the younger students have significantly enhanced the ability of my graduate and postdoctoral students to correctly assess the quality of their own and others' work.

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