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Reflections on Undergraduate Research Mentoring

Nicholas B. Whitticar[1,2,3], Craig S. Nunemaker[1,2,4,*]

[1]Diabetes Institute, Heritage College of Osteopathic Medicine, Ohio University, Athens, OH 45701, USA
[2]Department of Biomedical Sciences, Heritage College of Osteopathic Medicine, Ohio University, Athens, OH 45701, USA
[3]Translational Biomedical Sciences Program, Graduate College, Ohio University, Athens, OH 45701, USA
[4]Former high school physics teacher with K-12 certification at Clover Hill High School, Chesterfield, VA 23112, USA

As a former high school physics teacher, attracting students to consider careers in the science, technology, engineering, and mathematics (STEM) fields has been a long-term interest. Consequently, undergraduate students have often played prominent roles in my laboratory's research activities. Approximately 50 students have been involved in research in my lab either through summer research programs (including first-year medical students), for academic credit, as volunteer interns, or because of other academic requirements. Among those student researchers, 29 were coauthor on 1 or more peer-reviewed publications, with 12 students as first or co-first author. Many of these students went on to pursue postsecondary degrees in science or medicine. This report contains reflections and recommendations on motivating students to consider a career in the STEM fields from the perspective of a mentor and a doctoral student who began scientific research as an undergraduate.

High school students: exposure to real science

The concept of gaining new knowledge and exploring the unknown is fundamental to scientific pursuits, and so any opportunity to experience novel research is valuable. Laboratory activities that spark interest favor improved educational outcomes and retention in STEM fields (1, 2). One thing that can help students at the high school level to develop a better understanding of real-world science is to develop connections between high schools and local or regional colleges and universities. A few specific ideas for kindergarten through 12th grade educators, university investigators, or both to increase commitment levels include:

1. Initiate a partnership. Encourage professors, postdoctoral fellows, and graduate students to visit area high schools to describe their occupations. Take high school students on a field trip to see what a real-world scientific laboratory looks like (3). I offered to host a small group of entering first-year university students for a 30-min lab tour. Although evidence suggests that these informal approaches may not increase STEM participation (4), 2 of the 15

"*"corresponding author

students on that tour later decided to join the lab to conduct independent research projects.

2. Encourage one or two highly motivated high school students (recommended by their teachers as exemplary) to conduct a research project in a laboratory at a university or other institution (5). Studies suggests that this kind of unique research mentoring opportunity can motivate a high school student to seriously consider a career in the sciences (6).
3. Develop a lasting academic partnership. As a high school teacher, I had the unique opportunity to act as a faculty liaison for a course taught by world-renowned faculty at a nearby university for college credit on the "Pharmacology of the Brain" that was held at my high school and specifically designed for high school students. As another approach, an investigator could crowdsource data collection or analysis (7) to a classroom of high school students and provide a follow-up visit to the classroom to discuss the meaning and importance of the research.

Undergraduates at research-intensive institutions: involvement in meaningful work

From a student perspective, the quality and quantity of research going on at the university may not be apparent, highlighting the importance of promoting undergraduate research opportunities early in the academic career. Starting research efforts late in undergraduate training can limit project options and limit the potential for significant progress. From an investigator perspective, however, high-powered laboratories are not always interested in training undergraduates with little or no experience. In large labs with multiple postdoctoral fellows and graduate students, principal investigators may not directly train undergraduates but, rather, assign or delegate this responsibility to other members of the lab. Without direct faculty involvement, training may be inadequate, the project may not be well described, and the students could become disengaged from what they are doing. Recommendations for an enriching research experience for undergraduate students include the following:

1. Develop a project that is meaningful and valuable to the investigator and student. A student doing research for the very first time for a summer or a semester is not likely to complete a first author publication by the end. However, it is reasonable to expect that a student could master one or more straightforward techniques to collect and analyze enough data for a figure in a manuscript. In my office, I keep a copy of the very first study I was involved with because it was my very first scientific contribution. It still has a great deal of meaning for me even though I was a middle author.
2. Strive to teach from hypothesis to conclusion. Certain fundamentals of the scientific method hold no matter how big or small a project is: rationale/hypothesis, methods, data and analysis (results), and conclusion. I often quiz students about why they are conducting their study, what they expect to find (as well as what other results they could find), and what the results mean. A student who is excited and engaged in the work often comes up with "next step" questions, which is rewarding to the investigator and indicates that this student has a strong understanding of the project. These students are more likely to develop independence and to be productive in terms of research publications.
3. Not everyone is destined to be a scientist. A little more than half of the undergraduate students who enter my lab to conduct research ultimately become published authors; fewer go on to be researchers. The first-author students are almost always the students who devote substantial time to their research, sometimes coming in nights and weekends. They find value and enjoyment in what they do and often remain in science-related fields. Others leave after a semester, learning in the process of career exploration that scientific investigation is not their calling.

Undergraduates at institutions with fewer resources: add socioeconomic concerns to the mix

Our research success relied heavily on the substantial contributions of undergraduates. A vast majority of these students were either volunteers in the lab, took independent research credit, or both. These students were willing to be unpaid interns to get one-on-one training, research experience, and possibly publications. They could afford to do an unpaid internship to improve their medical or graduate school applications. However, this type of arrangement is being increasingly scrutinized (8) and may not work for many undergraduate students at many institutions. Additional considerations for undergraduate research opportunities in underserved rural or urban regions are as follows:

1. Make sure students have adequate resources outside the lab. Very few of the students I have mentored at Ohio University could simply volunteer in the lab over the summer. They needed the income to be able to afford to stay in town. From a student perspective, having funding available over the summer made it possible to work in the lab instead of taking a nonacademic job that would not add much to a curriculum vitae or medical school application. As with most academic institutions, numerous needs-based and academic opportunities are available at Ohio University, including the Program to Aid in Career Exploration, Summer Undergraduate Research Fellowship, Honors Research Apprentice Program, and Federal Work Study Program. Additionally, National Institutes of Health R15 training grants can provide funding for projects aimed at advancing undergraduate science education.
2. Make sure students understand their career options. Since coming to Ohio University in the heart of Appalachia, students have expressed concerns that although research is enjoyable, graduate school is not an option because they lack the necessary financial resources. This concern is borne out by a study of the rural Midwest (9). Many of these students are among the first generation to ever attend college, so the idea of paying for additional education seems like too big a burden on themselves or their families. The concept that tuition and a stipend are provided is inconceivable to many students. Colleagues are working to determine how widespread this misconception is in the region, but we suspect it is significant.

Final thoughts

Regardless of background or situation, certain students thrive on the scientific curiosity to discover new things. All they need is the opportunity to apply that curiosity to mentored research. A quote often attributed to entrepreneur Leila Janah states, “Talent is equally distributed, opportunity is not” (10). On the basis of research mentoring experiences at two very different institutions and a recent economic study (11), this quote rings true. Exceptionally talented students can be found anywhere. As mentors, it is incumbent upon us to provide the opportunity for students at all stages to participate and excel in scientific research.

To provide examples of the type of work that undergraduate students can achieve, we have included suggestions for assigning projects based on student situations (Table 1). References show the specific contributions that each undergraduate student made to the publication. Students will typically write the Methods and Results sections related to their figures, along with reviewing the final manuscript and revisions. Students who take a project from beginning to end will write the bulk of the manuscript with input from the mentor. From a student perspective, having the opportunity to get a publication was highly motivating. Explaining to students the importance of their part of a project and having publication as a goal gives the project meaning and lets them know their work is valued, which acts as an intrinsic reward.

Table 1. Suggestions for assigning projects to undergraduates based on time commitment.

Student situation	Duration	Type of project	Examples of published contributions
One or 2 semesters: A student conducts research to determine whether it is a good fit or to obtain research experience for medical school applications. Generally exploratory.	∼5 h/wk for 1–2 semesters Total: 50–150 h	Limited: student learns 1 or 2 techniques. Student may contribute data, analysis, or both for panels in a figure.	– Law (12, fig 6B): Learned to image and quantify NAD(P)H. – Bogart (12, fig 2): Having prior experience, student conducted a defined project of data collection and analysis. *Students do not necessarily publish because of the brevity of the experience.*
Summer research start: A student volunteers or works through a summer program. A great way to build skills and independence and to initiate a long-term research commitment.	∼20–30 h/wk for 10 wk Total: 200–300 h	Students should have enough time to conduct several different studies related to a topic and master at least 1 methodology.	– Ramadan (13, fig 1; 14, fig 3; 15, first author): Learned calcium imaging to contribute to several papers. – Whitticar (16, first author): Designed and assembled a dual-syringe automated perifusion system. *Focused effort during summer enhances productivity and leads to independence for subsequent studies.*
Multiyear research: A student works on a research project for up to 4 y, often ending in an honors thesis.	Summer(s) and multiple semesters Total: >500 h	Projects can be open-ended. Proposals are often written in advance. Weekly meetings.	– O'Neill (14, first author; 15, coauthor) – Qureshi, Dejene (17, co–first authors) – Waters (12, coauthor; 18, co–first author). *Each student conducted a large amount of the work for their project over an extended period of time.*

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