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Commentary

Nurturing Undergraduate Researchers in Biomedical Sciences

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https://doi.org/10.1016/j.cell.2020.05.008

Undergraduate researchers are the next-generation scientists. Here, we call for more attention from our community to the proper training of undergraduates in biomedical research laboratories. By dissecting common pitfalls, we suggest how to better mentor undergraduates and prepare them for flourishing careers.

Fostering the Next Generation

Nurturing next-generation researchers is a central mission of our biomedical science community. The vast majority of practicing scientists in academia started doing research as undergraduate students. Probably by chance and luck, some of the successful researchers had great mentors who inspired them with the beauty of science and taught them solid research skills. However, when we talk about "the next generation" these days, we most often refer to graduate students and postdocs and usually neglect undergraduate students, many of whom work hard in research labs and will become eventual PhD and/or MD students. This general neglect originates from a common mindset that undergraduates are not genuine trainees but only "second-tier" lab assistants. As a result, they are often placed on repetitive, boring, and labor-intensive tasks. Other labs may simply say "no" to undergraduates because of the misconception that undergraduates do not devote sufficient time to research to be worth training. These obstacles can turn potential budding scientists away from pursuing research, often permanently, which goes against our mission of attracting brilliant young minds into biomedical research.

Unlike the training of graduate students or postdocs, mentoring of undergraduates in biomedical labs is rarely discussed. Many undergraduates are trained primarily by graduate students and postdocs (referred to as "junior mentors" hereafter), who are still seeking their own paths in science and often have minimal mentoring experience. Consequently, the training an undergraduate receives is highly dependent on the motivation, ability, knowledge, and personality of the junior mentor. Poor training at this beginning stage is particularly harmful. We have seen many junior graduate students suffering from substandard research habits or scientific judgment, likely carried over from their undergraduate years, which severely impedes their success and increases their likelihood of quitting science. Most critically, poorly trained scientists are unlikely to be good mentors in the future and may provide substandard coaching to their own trainees, creating a vicious cycle of poor mentorship (Figure 1, left). It is undoubtedly much better to train undergraduates properly from the very beginning than to fix problems at later stages of their career.

Proper training of undergraduate researchers takes time and effort, but we believe that such time and effort are well worth spending and provide huge benefits. First and foremost, it attracts talented and creative young minds into biomedical research and lays a solid foundation for their future success. Second, it provides an invaluable opportunity for junior mentors to develop teaching and motivational skills with guidance from their lab heads, which fosters the junior mentors' own career development and success. Third, even from a more "shortsighted" perspective, well-trained undergraduates can contribute a lot to the lab, which accelerates research progress as observed in our own lab. Thus, fostering undergraduate researchers by providing them with solid training creates a virtuous cycle that benefits everyone in the biomedical research community (Figure 1, right).

Here, we present our perspective on how to better mentor undergraduates. Since most undergraduates are mentored by graduate students and postdocs, we target our suggestions to these junior mentors. Some of these points also apply to lab heads who directly teach and train undergraduates. In the Text Box, we highlight some advice for undergraduates.

Junior Colleagues, Not Laborers

The most common problem in training undergraduates is their treatment as cheap labor for repetitive and time-consuming lab work. Although everyone starts with basic techniques and masters these skills through repetition (an indispensable process that we will emphasize in the next section), lab heads and junior mentors should inspire undergraduates with the beauty of science and the wonder of discovery and provide them with comprehensive scientific training similar to that of graduate students. They should avoid using undergraduates as merely pairs of hands.

Clarify Research Rationales and Key Methodologies

Before assigning an undergraduate dozens of genotyping PCRs or the like, a junior mentor should first arrange a well-prepared discussion (like those with the lab head or advising committee) on the project's background, rationale, and scientific goals, as well as the mechanisms of key methods. These discussions put the experiments the undergraduates are about to perform in the larger perspective and should help

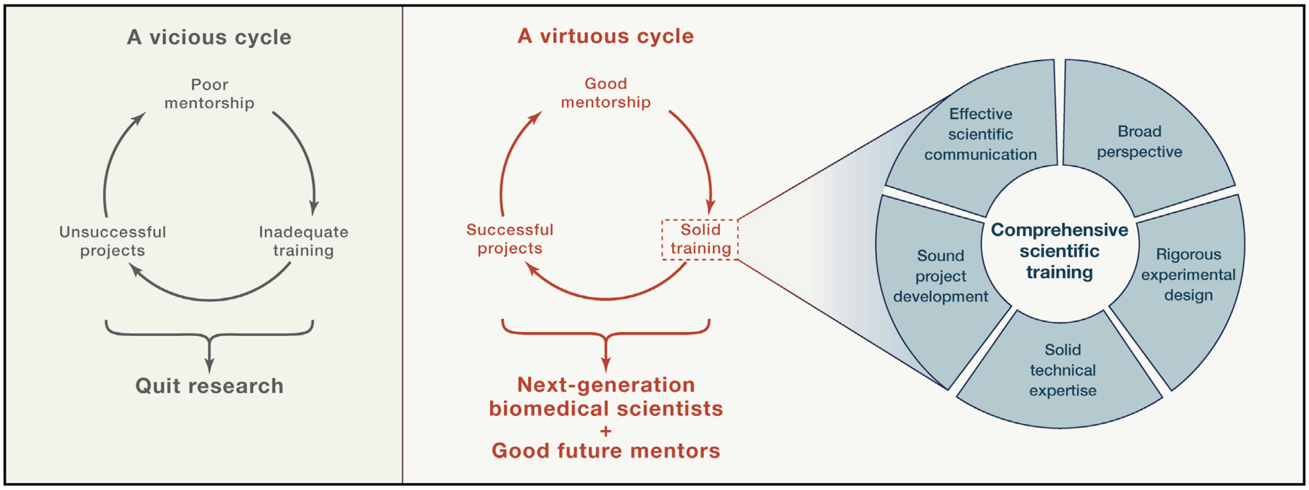

Figure 1. Fostering a Virtuous Cycle with Good Mentorship Instead of a Vicious Cycle
Left, neglecting mentorship of undergraduate researchers can create a vicious cycle. Right, nurturing undergraduate researchers with comprehensive scientific training fosters the next-generation scientists of biomedical research and produces good future mentors.

convince them that this direction is worth pursuing. If junior mentors cannot convince their undergraduates, it is probably the time for the mentors to reconsider the direction or reflect on their own communication skills. We encourage undergraduates to fearlessly ask questions and challenge your mentors until every puzzle in your mind is resolved. Lab heads and junior mentors must remove any hierarchical mindset and treat our beginner scientists as colleagues rather than "second-tier" laborers. Display your knowledge and scientific thinking by addressing all of their questions instead of dictating! This exercise not only benefits undergraduates' education, but also safeguards the research itself. Without knowing the rationale of an experiment or the mechanism of a method, undergraduates (as well as anyone else) may frequently make mistakes without being aware of it. Based on our own experience, mistakes caused by lacking a piece of basic knowledge or presumed "common sense" are most difficult to detect and could consume lots of time for troubleshooting. It ultimately saves time by thoroughly teaching undergraduates from the very beginning.

Get a Broad Perspective from the Literature

Among junior graduate students, we have often seen a common type: hardworking, proficient at a number of techniques, but lacking a broad view of the field. This is usually caused by an imbalanced training in their undergraduate years: nothing else was taught except a few techniques that their junior mentors wanted someone to help with. To accumulate knowledge and thus build a big picture of a field, the most effective way is to read papers. While many universities have seminar classes emphasizing primary literature, these classes often enroll a small, select cohort and normally prioritize graduate students. On the other hand, it may be intimidating and frustrating for undergraduates to start reading primary research papers by themselves. Junior mentors should guide their trainees into the world of scientific literature by thoroughly dissecting selected papers with an emphasis on how each individual experiment contributes to the overall discovery. Three types of papers provide a great start: (1) research articles closely related to the ongoing project, which provide the background and describe commonly used approaches; (2) balanced and comprehensive reviews with a broad scope covering the relevant field; and (3) classic landmark papers with brilliant experimental designs and far-reaching impact. Extending from this, undergraduates should learn how to explore and select relevant papers from the ever-expanding literature and routinely discuss them with their mentors. When our undergraduates have discovered and shared with us important papers that we ourselves missed, we know that we have achieved a milestone.

Foster Effective Scientific Communication

Undergraduates deserve better training in scientific communication and more opportunities to present their own research. Lab heads should invite undergraduates to attend all lab meetings and thus broaden their views to various topics in the lab instead of confining them exclusively to their junior mentors' research. Undergraduates, particularly when completing their full-time summer research, should be given opportunities to present formal lab meetings with the same standard as graduate students

Text Box: Tips for Undergraduates

- Understand the rationale and methodology of your experiments.
- Ask questions and challenge your mentor until every puzzle in your mind is resolved.
- Master technical skills through iterative and patient practice.
- Learn how to develop and move forward with a project.
- Practice communication skills and present your discoveries publicly.
- Expand your scientific horizon by reading papers and by attending seminars.

and postdocs. We find that involving undergraduates in lab meetings is a remarkably effective way to improve everyone's presentation skills. Instead of simply enumerating data, graduate students and postdocs need to better prepare the background and rationale so that our newcomers can comprehend their research. It also forces junior mentors to better train undergraduates, as it would surely be a shame if one's trainee only showed hundreds of DNA gels without discussing why certain experiments were done and what the results mean. As discussed below, institutions, conference organizers, and scientific societies should create more opportunities for undergraduates to present their discoveries publicly. Bringing undergraduates onto the presentation stage is a recognition of their efforts and encourages them to continue their journey as researchers.

Notably, a complete and balanced scientific training in the undergraduate years is just as important, if not more, for those choosing to be physicians without running research labs of their own. Knowing how research is conducted and how to effectively communicate with basic scientists will facilitate translational and clinical studies through collaborations with their peer scientists. It would also be of great value to undergraduates who later become attorneys or policy makers to better understand how scientific research operates.

Solid Research Skills

Working with successful junior mentors can be a double-edged sword for undergraduates. It could be an encouraging and productive journey, as mentors make progress and procure high-profile publications on the way. However, staring at a glowing star often causes illusion. Undergraduates may not see the long struggling hours (or years) of their mentors and thus underestimate the difficulty behind scientific discoveries. Indeed, undergraduate mentees may get lost in the easy success and neglect to develop solid research skills, setting up a ticking time bomb in their career. Because of their (in fact, their previous mentors') performance, these students are enriched in competitive graduate programs. Their confidence at the beginning often masks the discrepancy between their self-perception and true ability, making it difficult to detect by themselves and their mentors. Unfortunately, they may not be as capable as they think to run research projects independently. Failures emerging from choice of directions, project development, and technical skills burn their time, erode their confidence, and cause some to abandon research permanently unless their mentors promptly intervene. This time bomb set by an effervescent undergraduate experience is ultimately destructive. Rather than leaving a time bomb for the future, lab heads and junior mentors should provide undergraduates with solid training on research skills and thus build their confidence on a firm foundation.

Acquire Technical Expertise

While undergraduates should never be treated as merely pairs of hands, proper technical training cannot be omitted. On the contrary, it is particularly important for undergraduates to develop solid technical skills. As every experimentalist knows, reading a protocol or watching someone else do an experiment cannot transform the protocol into one's own expertise. Practicing it (often repeatedly) by oneself is indispensable. After describing the experimental rationale and technical background, junior mentors should guide their undergraduate mentees to do every step by themselves and, importantly, anticipate that they will make mistakes. When a mistake occurs, instead of taking over the rest of work furiously, junior mentors should dissect the mistake together with their mentees and figure out how to avoid it in this and other similar experiments in the future. At the same time, undergraduates should focus and be patient when trying to master an experimental skill, quite similar to learning an instrument in childhood; asking any questions you might have can help minimize errors. A skill is not satisfactorily acquired until the undergraduate can conduct the entire experiment flawlessly without the mentor—a simple criterion to determine the efficacy of any learning process. Only with solid technical execution (as well as appropriate control designs discussed below) can one's experimental results be interpretable and thus contribute to knowledge. It is thus crucial for undergraduates to hold to the highest standard on technical skills and develop good research habits from the very beginning.

Learn to Design and Manage Projects

Experimental design and project management are often missing from undergraduate training, mainly because their lab work is usually defined by individual experiments rather than a complete scientific project. Even though such training is extensively provided in graduate school, undergraduates can greatly benefit from learning this earlier. As discussed above, understanding the rationale behind each experiment helps undergraduates comprehend the scientific goal and thus reduce mistakes when they conduct experiments. Moreover, realizing that technical expertise is necessary but insufficient to succeed in science also urges them to purposefully expand their skill repertoire such as project development and scientific communication, which will facilitate their long-term career success. To incorporate these topics into undergraduate training, the most effective way is to give them a small project and let them run everything with guidance and necessary assistance from junior mentors. Such a ''miniature'' project can be a part or an extension of the mentor's major project but stands on its own. Running a project semi-independently motivates undergraduates to take intellectual ownership and, should the project be successful, significantly boosts their confidence in conducting research. At the very least, undergraduates will acquire a complete set of research skills and learn how to troubleshoot when unwelcome surprises arise.

However, an undergraduate may not have enough time to run an entire project due to coursework and other activities, and there may not be a suitable mini-project at a given time. In these cases, junior mentors can regularly (e.g., weekly) discuss with undergraduates the progress and current difficulties of their own project so that undergraduates can follow the complete history of a project in addition to contributing to a few experiments. Although not ideal, being ''sightseers'' can inform undergraduates how a project is developed and how its experiments are designed by integrating previous knowledge and new results. In these discussions, junior mentors should explain the rationale of each experimental design and the reason behind each choice of controls, especially how each control is indispensable for interpreting the results. It is also particularly informative to write down all alternative paths that the project can follow and review why a certain path is chosen but not the others. This teaches undergraduate mentees how to generate interpretable data and how to use them to inform future directions of a project. Together with technical expertise, these skills lay a firm foundation for undergraduates and thus grant them confidence based on their own abilities.

Training for Novice Mentors

Good scientists are not necessarily good mentors, and no one is born with mentoring skills. Like doing research, becoming a good mentor requires learning and practicing. Training undergraduates provides an invaluable opportunity for postdocs and graduate students to learn how to be mentors and how to manage mentees' research; this is one of the most important jobs they will have as future lab heads. Even if they choose non-academic careers, these skills are essential for teamwork and management. In addition to teaching undergraduates scientific knowledge and research skills, junior mentors should also learn how to motivate their trainees, especially when they are frustrated by disappointing results.

Letting undergraduates do experiments independently or run an entire mini-project can often cause uncertainty and anxiety for junior mentors. Are they messing up everything? Are their results trustworthy? However, junior mentors must realize that it is impossible to do or track every single experiment by themselves after they become lab heads. Rather than postponing this problem, they should think about the essentials that they need to keep an eye on and figure out how to ensure research quality while giving trainees a certain degree of independence. Luckily, junior mentors can seek help and get feedback from their lab heads—another reason why postdocs and graduate students should learn to mentor early (you are not completely on your own!). Lab heads should pass on experience, particularly past lessons learned, to the novice mentors and give them advice when detecting problems in their mentorship, propelling a virtuous cycle of good mentorship (Figure 1, right).

Call for More Opportunities

Fostering undergraduate researchers requires not only the effort of lab heads and junior mentors but also support from institutions, funding agencies, and scientific societies. Summer undergraduate research fellowship programs in many institutions provide a great entry for undergraduates to get into research labs and often seed their long-term affiliation with those labs. It is particularly fruitful to organize regular lunch gatherings and poster sessions to encourage undergraduates to present their own discoveries. This also pushes their hosting labs to do a better job training undergraduates, who will represent their labs publicly. Extending from the summer programs, institutions should encourage undergraduates to attend regular academic events, such as seminars and symposiums. Even though they may only digest a fraction of the content, research seminars broaden the scientific scope of undergraduates and thus help them develop their own research interests.

It is also not common for undergraduates to attend scientific meetings, primarily due to a lack of funding to cover their registration and travel costs, unless their lab heads are well-funded and unusually generous. Unlike those for graduate students and postdocs, we are not aware of fellowships or department funds specifically designated to support undergraduates to attend scientific meetings. However, we know many brilliant undergraduates who have made remarkable scientific findings and deserve to share them with a broad audience. It would be a great loss if they cannot do so due to lack of funding. We therefore encourage conference organizers and scientific societies to set up competitive awards to bring outstanding undergraduates to scientific meetings and give them more opportunities to present their own discoveries.

By welcoming undergraduates into biomedical research communities with open arms and nurturing them with proper training, we can build a more sustainable research community with thriving next-generation scientists.

ACKNOWLEDGMENTS

We are grateful to many undergraduates in our lab who have made substantial contributions to our research in the past 23 years and to Stanford Summer Research Programs for supporting them. We thank M. Chen, X. Gao, R. Guajardo, J. Kebschull, H. Li, Z. Li, N. Nguyen, J. Ren, A. Shuster, Q. Xie, and C. Xu for comments. J.L. gratefully acknowledges L. Luo, Y.-N. Jan, L. Y. Jan, W. Zhang, G.-S. Feng, S. Li, X. Xiao, F.-P. Wang, Y. Zhang, and W. Xia for their mentorship; Zhiyuan College of Shanghai Jiao Tong University for undergraduate education; and R. Guajardo for working with J.L. and contributing enormously to the research. We thank the National Institutes of Health, the National Science Foundation, and Howard Hughes Medical Institute for supporting our research.