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PERSPECTIVES

A Graduate Student's Mentorship Pedagogy for Undergraduate Mentees

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Abstract

Evidence has shown that primary mentors' actions and pedagogy have a direct impact on undergraduates' experiences in research programs. Although there are an increasing number of studies investigating faculty mentorship of students, graduate students as the primary mentors of undergraduate research is often considered less within the literature, and additional resources to improve the development of graduate students as effective mentors are needed. Graduate students positioned as the primary mentors can offer unique benefits to undergraduate biomedical researchers in terms of availability, career or technical support, and insight into postgraduate education. These aspects have been shown to positively correlate with undergraduate experiences in academic research programs. However, many graduate students have little experience directly mentoring others and require guidance to develop into an effective mentor. Therefore, this article offers strategies for graduate students to best prepare and transition to a new supervisory role. In this article, a biomedical engineering graduate student's implementation of evidence-based methods and pedagogy on effectively mentoring undergraduate mentees for short-term research experiences is discussed. Also included are teaching tools for graduate mentors and supplementary resources, which can be provided to undergraduate mentees.

Keywords Mentorship · Graduate student · Undergraduate research · Undergraduate mentee · Pedagogy

Introduction

Undergraduate research experiences, such as summer internships or the National Science Foundation's REU programs, have been regarded as a high-impact educational practice [1] through which student retention and success are increased within the sciences [2–4]. Students engaging in undergraduate research obtain valuable learning outcomes that can have lasting influence throughout their professional career. Research opportunities are becoming an increasingly integral part of the undergraduate curriculum with institutions initiating programs to better fit student needs [5]. A key element for successful undergraduate biomedical engineering research is the involvement and mentorship by more experienced scientists. Outcomes of undergraduate research have been shown to be dependent on the quality of mentorship, where the highest impact occurs when mentors can effectively lead their mentees from relative dependence to guided autonomy over the course of a project [6]. Specific actions of the primary mentor (e.g., preparing for the mentee's arrival, being readily available to the mentee, and proactively monitoring the student's progress) have been shown to positively correlate with undergraduates' research experiences and research output [7, 8], demonstrating the importance of a well-prepared and trained mentor.

While faculty hold a large role in student research, undergraduates often interact primarily with graduate students, particularly at research-intensive institutions [7, 9–12]. Through these supported opportunities, graduate students can gain mentorship skills, which are often sought for future faculty positions but are undertaught in postgraduate training [13, 14]. Moreover, literature resources aimed specifically at the role of graduate students as mentors are sparse despite the prevalence of graduate students serving as primary mentors to undergraduates [15]. Crais and Savage found that in a sample of 226 doctoral students, only 54% felt well prepared to mentor students and a majority indicated a need for more effective teaching preparation [16].

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Having few opportunities to mentor others, novice graduate students may develop their mentorship pedagogy by learning through immersion, which can often create numerous challenges and ultimately result in a disservice to both the graduate mentor and undergraduate mentee. Therefore, more resources are needed to prepare graduate students to act as quality research mentors and to provide support in the transition to their new supervisory role.

To help improve the development of graduate students as research mentors, this article discusses a biomedical engineering graduate student's implementation of evidence-based methods and pedagogy on effectively mentoring summer undergraduate students. While this article is focused on short-term, summer experiences, the methods presented within are applicable to all lengths of research experiences, especially when an undergraduate first begins in a laboratory group. Several aspects unique to the role of graduate students as supervisors are highlighted within, including (1) core goals and benefits of mentorship, (2) transitioning to the new role of middle manager within a triad, (3) strategic project pre-planning and training, and (4) providing opportunities for career development. Additional recommendations and resources for graduate students to aid in pedagogy development are included.

Core Goals and Benefits of Graduate Mentorship

Key reasons to mentor vary among those at different career stages [17], but mentorship ultimately results in a reciprocal relationship between mentor and mentee. The benefits of effective research mentoring are well established and should produce multiple benefits and outcomes for each person within the network [18]. A majority of the discussion about undergraduate research often focuses on the outcomes of a successful program from the perspective of the mentee. However, there are advantageous reasons to appoint a graduate student mentor, which are often less discussed. As undergraduate research programs grow within institutions, the ratio of faculty to undergraduate mentees progressively decreases [19]. Additionally, faculty have many institutional responsibilities, which limits their time dedicated to supervising and training undergraduates [20–23] and can impact students' experiences negatively [24]. Undergraduates often begin biomedical engineering research training programs with expectations that they are able to meet regularly with their mentors and be offered guidance when needed. Faculty with many commitments may have limited time and, therefore, cannot foster the career or technical support that the undergraduates may be expecting. By appointing a graduate student as primary mentor, undergraduates receive guidance from a person who is easily accessible and whose main focus is laboratory work. This arrangement also allows graduate students to actively gain experience and learn mentorship skills from faculty via a vertical mentorship model. The faculty advisor's role is to form mentor–mentee pairs, establish the tone of the mentoring relationship, and also serve as a mentor and role model for both the undergraduate and graduate student [18]. Over the course of postgraduate programs, graduate students are able to have the opportunity to mentor multiple undergraduates and gain repeated practice of their developing mentorship skills under the guidance of experienced faculty advisors and other senior graduate students. By appointing a graduate student mentor, the undergraduate, postgraduate, and faculty all are beneficiaries from the relationship in terms of skills, career development, and research productivity.

Benefits to Graduate Students

As early career researchers, many graduate students are driven by both intrinsic and extrinsic reasons to dedicate themselves to mentoring. Personal fulfillment, enjoyment of teaching [8], and the desire to develop the broader scientific community [17, 25] have been found as intrinsic reasons for graduate students wanting to engage in research mentorship. Additionally, many use the educational opportunity for career development, where mentorship skills and pedagogy can be formed with the aid of their faculty advisor (Fig. 1). This allows faculty to guide the graduate mentor through a hands-on learning experience as the student develops and refines their leadership and mentorship skills. These valuable, professional skills include interpersonal, communication, leadership, time management, critical thinking, teamwork, and project management skills [26]. Actively attaining these skills is an advantage that can increase the student's marketability for both academic and industry positions [27].

Extrinsic reasons for mentoring an undergraduate researcher mainly pertain to academic productivity. Graduate students have listed both the ability to re-learn basic research skills and techniques alongside the undergraduate [25] and to acquire a deeper understanding of scientific concepts through teaching [17] as motivations to mentor. Additionally, undergraduates that join a research team predominantly aid in the day-to-day operations of laboratory work and their research efforts are usually contributions to the graduate mentor's research project. Mentees are ideal for assistance in implementing repetitive or simultaneous protocols for data collection, performing basic data analyses, or drafting scientific figures. The culmination of these benefits can dramatically increase the graduate student's research productivity, overall academic performance, and success [28].

However, there are costs to the graduate student mentor associated with training and supervising an undergraduate.

Fig. 1 Stages of graduate students becoming effective mentors

A significant investment in time and effort is warranted to effectively mentor novice researchers, especially at the beginning of the relationship. Most undergraduates enter academic research with little to no knowledge of the scientific field or techniques used within the laboratory. Devoting the energy to plan a project, train, and supervise an undergraduate can be a substantial time commitment for a graduate student. This may result in early challenges, such as reduced research productivity, limited time management, and reconciling the roles and responsibilities of personal work load with those of being a mentor [29]. As graduate students adapt and learn their new role, these costs have been shown to decrease as the undergraduate grows in competency and relative autonomy. Considering these factors, one should reflect whether they are at a point within their postgraduate training to be able to take on these difficulties without harming the experience of the undergraduate mentee.

Benefits to Undergraduate Mentees

By joining a laboratory group, undergraduates are gradually introduced to a specific biomedical engineering field under a mentor's guidance. Throughout the experience, they progressively develop into a professional with an identity among the larger biomedical research community [30]. There is a large body of literature investigating the benefits of research mentorship for undergraduate mentees [31–34]. The main benefits for the undergraduate include a higher grade point average (GPA) compared to those not involved in research [35–37], an increase in confidence and understanding of the research process [38], professional network growth, more competitive graduate school applications, and clarification, confirmation, and refinement in their professional career path trajectory [31]. Additionally, undergraduate mentees gain skills that are highly valued both in industry workplaces and in preparation for graduate school applications [39]. These skills include technical skills, experimental design, inter-team collaboration, problem-solving, critical thinking, and scientific communication.

As opposed to faculty, there are unique benefits to the undergraduate by having a graduate student mentor. Studies have found that undergraduates consider postgraduates more approachable and less intimidating than faculty [18]. This allows for improved contact and communication to keep research projects on track and mitigate the absenteeism some may experience from a primary faculty mentor. Additionally, graduate students can provide personal insight into the graduate school experience. By discussing the day-to-day life and expectations of graduate school, this broadens undergraduates' understanding of the application process and scientific training that occurs in graduate studies [18]. These discussions help undergraduates realize the expectations and attributes necessary for masters or doctoral work and whether the pursuit of biomedical engineering graduate education fits their personal and professional goals. This side-by-side experience is particularly impactful for under-served communities of students deciding to proceed within academia, especially persons excluded because of their ethnicity or race (PEER) [36, 38, 40–44]. Research has shown that the establishment of professional connections via building social capital from mentors' resource networks encourages interest and persistence in STEM for PEER groups [45–47]. Therefore, the utilization and maintenance of social capital accessed from the research group's connections is a key element for mentees who may be interested in academia [48].

Moreover, undergraduates are typically assigned work that pertains to the graduate student's project. Thus, undergraduate mentees are held responsible and are actively contributing to a component of a larger project, which supports the notion that their contributions are meaningful and provide value to the research group [49]. Graduate students can provide a direct relationship with a mentor and meaningful work, which are two positive, important elements undergraduates seek in biomedical research opportunities [50].

Functioning as a Middle Manager

Traditionally, training within academia is often conducted as a cascading apprenticeship model taught by a more-experienced mentor to a less-experienced mentee [51]. However, biomedical engineering research today frequently occurs within teams, and students rely on multiple people for learning and support. In the context of undergraduate research, the cascading mentorship model often results in the formation of undergraduate–graduate student–faculty triads rather than an undergraduate–faculty dyad [11]. Graduate students who mentor undergraduates are themselves mentored by a mutual faculty advisor [9], creating a multi-mentor model in the form of a triad. The integration of graduate students into mentorship triads can exist in many forms depending on the strength of relationship ties between each member. The most common is the closed triad, where the undergraduate has direct relationships with both the graduate student and faculty member [11]. The closed triad model is an interdependent, developmental relationship that promotes mutual growth, learning, and career development for all members, unlike the traditional one-way, cascading apprenticeship model. In both of these models, graduate students are placed in a unique position dynamically between the faculty member and the undergraduate mentee, holding a role as a direct supervisor of the undergraduate. Undergraduate mentees can benefit to a greater extent within a closed triad than the traditional hierarchical mentoring relationship. Accounting for limitations in hierarchical mentoring, the implementation of a collaborative mentorship triad can provide learning experiences within multiple zones of proximal development [52] and connections to various social capital sources [53].

The transition to the role of direct supervisor can be challenging for graduate students, even with the support of a faculty advisor (Table 1). By functioning as a middle manager between the faculty advisor and undergraduate mentee, it is imperative that the graduate student aligns and understands the faculty advisor's expectations of both themselves and the

Table 1 Resources for graduate students

Category	Description of key concepts	References
Mentorship	Discussion of significant attributes of exemplary mentors from young research mentees with inclusion of a self-assessment for reflection	[84]
	Discussion of ten important practices of award-winning mentors based in literature research	[85]
	Curricula and training resources for entering mentorship for various research disciplines denoted by career stage of the mentee	[86]
	Workshop recording from the NIH *Becoming a Resilient Scientist* series discussing various aspects to participating in a mentoring relationship, including running meetings, solving conflicts between members, work style differences, expansion of the mentorship network, and managing up	[87]
	Self-assessment to evaluate six competencies of mentorship, including effective communication, aligning expectations, assessing understanding, addressing diversity, fostering independence, and promoting professional development	[88]
	Provides guidance about conflict resolution in a mentored relationship with examples of how to manage interactions and suggestions for mentees to proactively promote beneficial dynamics	[89]
Creating protocols	Details the format, structure, components, and considerations to include for a detailed research protocol with examples	[59, 90]
Teaching R	A step-by-step resource of how to teach R in a workshop style with common issues of first-time students, code examples and exercises, and teaching schedule	[91]
Teaching scientific writing & manuscript preparation	Discussion of barriers of undergraduate publication and 5 best practices to successfully mentor students to first authorship	[92]
	Article detailing the "Results Formula Approach" to teach students to write an effective Results section	[93]
	Teaching resource that discusses the value of undergraduates publishing with decision trees to determine whether publishing is an attainable goal for the project, whether the student has earned authorship, and whether they should serve as first author. Also included are recommended strategies for publishing with undergraduates.	[94]

undergraduate before training begins. Several expectations should be outlined between the two before the undergraduate is introduced into the triad. Frequency of meetings and who should be involved (i.e., graduate student with the mentee, graduate student with the faculty advisor, mentee with the faculty advisor, or all three members within the triad simultaneously) should be established and scheduled in advance. The graduate mentor and faculty advisor should also discuss what laboratory techniques the undergraduate will be trained on. This allows the opportunity to align mentoring methods and philosophies between the two. Lastly, the duties and responsibilities that the graduate student holds as a project supervisor should be discussed. This will allow for a smooth transition for the graduate student to their new supervisory role.

As middle manager, the graduate student should meet frequently with the faculty advisor to discuss the undergraduate's research progress. The graduate student should update the faculty advisor on how training is progressing and any data the undergraduate acquires or presents. Frequent updates allow for discussion about any problems or setbacks occurring and provides the opportunity for the faculty advisor to give guidance on how to remediate issues, tips on teaching, and strategies for mentee success. Importantly, accomplishments of the undergraduate should also be relayed in these meetings. This continued discussion of the undergraduate's progress is a critical element, especially for students partaking in credit-earning research experiences. For these students, faculty advisors will ultimately score their efforts, and clear communication of expectations, progress, and outcomes of the undergraduate is warranted between all members within the triad.

Strategic Pre-planning of the Research Project

A vital step for graduate student mentors in undergraduate mentorship is the pre-planning of the project that mentees will be expected to complete. Selection and planning of the research project before the undergraduate starts is an important task to set both the mentor and mentee up for success, especially for shorter summer research experiences. Undergraduates can vary widely in terms of their preparation, motivation, knowledge, and skills when entering academic research. Thus, it is important to tailor the selection and scope of the project to the individual who will be mentored [54]. There are several aspects to consider for intentionally preparing a research project for a mentee. The first is to conceptualize a project that is at a level the undergraduate would be capable of understanding. Forming a project that the mentee is able to scientifically comprehend is crucial for them to understand the scope of the research and either the hypothesis or engineering design problem they are investigating. The research scope can differ for undergraduates earlier in their degree progression than those who are in their final years, and the graduate student mentor should account for academic courses that the mentee has completed, such as statistics, computing and data analysis, biology or chemistry laboratories, fluid dynamics, material science, or engineering design courses. The foundation of the undergraduate's understanding of concepts or skills gained through these courses is essential to factor into the scope, especially for projects centered around engineering design and optimization. Another characteristic to consider is to draw on technical skills the student already has or can easily learn. Often times, undergraduates are new to laboratory research and hold few to no technical skills, necessitating that a substantial portion of the undergraduate research experience is in technical skills training. Building a project around skills that are already held or can be quickly attained is necessary to attain a feasible research project that can be completed within the predetermined timeframe. A technical skill dry labs could consider for each mentee is whether the undergraduate has experience with the coding language used for in silico work and what their proficiency level is. For wet labs, a technical skill to consider is whether the undergraduate has had previous cell culture experience. If so, the training may be planned starting with the culture nuances of the cell type or line used in the group. Otherwise, the undergraduate's training would require beginning with proper aseptic technique. Tangential to technical skill requirements, the undergraduate should be able to produce results within the allotted timeframe. Undergraduates are generally involved in laboratories for a pre-established time. Whether the undergraduate plans to participate in biomedical research for a summer term, a semester, or longer throughout their baccalaureate studies, the project should be able to be completed in the predetermined amount of time. This supports the undergraduate mentee to progress in both their skills and data analyses [55]. The last consideration in pre-planning is that the project should span a reasonable scope while having the ability to be shortened or extended [56]. Having the ability to simplify the scope can be a safeguard in the case methodological troubleshooting needs to be performed or if the student is not progressing as originally expected. Yet, if the outlined scope of the project is completed early or if the undergraduate wishes to continue the research beyond the initial experience, the ability of the project to be extended beyond the original depth and breadth is valuable. Graduate students should work with their faculty advisor to form a research project based around these considerations.

Once the scope of the project is defined, the graduate mentor should begin preparing several materials the undergraduate will need for their training. The first is an outline of the project time table [57, 58]. The time table should not only include the approximate time the research project should take but also account for orientation to the laboratory, building of background knowledge, training, active data collection and analyses, and assembly of final projects to present and disseminate data (Fig. 2). Investing the effort to create a detailed time table from start to finish of the research project will help align faculty expectations of the undergraduate as well as help the undergraduate keep track in their progression. Next is the essential preparation of background resources. Often, undergraduates are entering an area of research for the first time and have little to no prior knowledge surrounding the topic. Background resources should discuss key terms and explain important ideas in lay language as the mentee may not understand the terminology common within a particular biomedical field. These resources may be composed of selected sections of literature articles, textbook chapters, grant proposals, websites, or a focused presentation by the graduate student. Additionally, either a summary of the laboratory group's current scientific direction or background of the aims of the graduate student's dissertation research are particularly helpful in contextualizing the undergraduate's project within the larger research scope. Background resources should describe the project's objective in terms of both engineering and biology aspects and explain the biologic disease and clinical significance of interest. Dry lab groups should include process flow diagrams, boundary conditions, and constraints to explain the applied computational analyses performed in the lab. Lastly, the graduate student should prepare pre-written, thorough protocols that the undergraduate will use for the project. Protocols are one of the first steps in training good scientific practice and the foundation of research project success [59]. If technical protocols exist in the laboratory at present, the graduate student should determine whether a more detailed protocol would be beneficial to the undergraduate mentee. By writing and organizing extensive protocols, the graduate student mentor is able to assemble a powerful resource to which the undergraduate mentee can reference. The beginning of each protocol should list the objective of the experiment, supplies and reagents required, as well as their

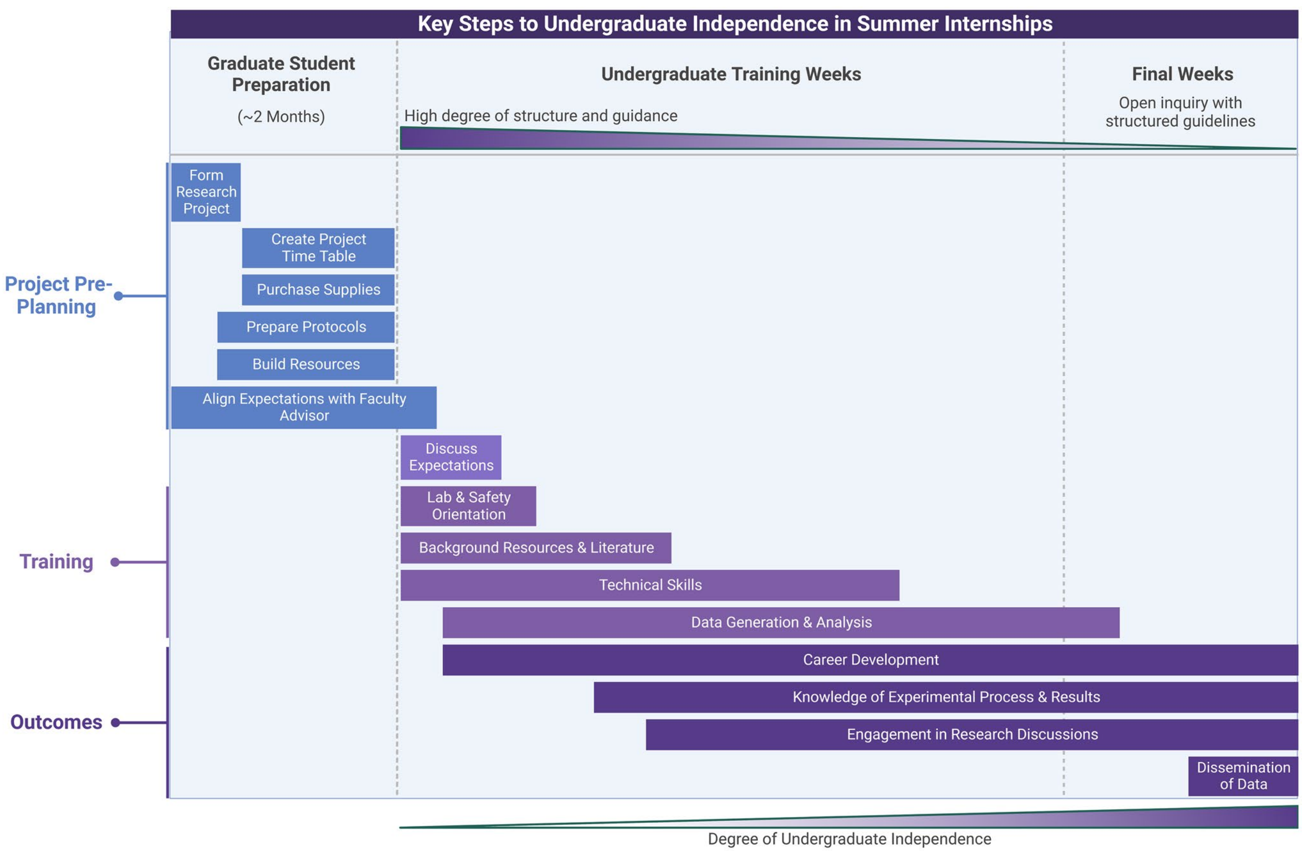

Fig. 2 Timeline of key steps leading to undergraduate independence in a summer research internship. Bars indicate key steps, as applicable for wet versus dry labs, essential for effective mentorship within the undergraduate research timeline. Colors represent different training stages with details in the bars described in the text. The gradient at the top represents the amount of structure and guidance the graduate student mentor gives the undergraduate mentee over time. The gradient at the bottom represents the degree of undergraduate student ownership and independence over time

location within the laboratory, and experimental controls. The body of each protocol should consist of comprehensive steps to be performed, written in a step-by-step format. By doing so, the graduate mentor is able to think through the experiment from a mentee perspective. This helps to identify the most critical steps within the protocol and where the mentee may struggle. The addition of images paired with protocol steps is also useful, especially for software-based methods. If common problems typically occur, the protocol should include a troubleshooting section detailing how to identify issues and methods to remediate them. Lastly, the protocol should provide information on data management and analysis. Statistical methods used for data analysis should also be clearly outlined [60]. Any supplies required for the project should be procured before the mentee begins, to avoid unnecessary delays in a short-duration experience, such as a summer internship.

Technical Skills Training

Before the undergraduate begins hands-on work in the laboratory, the graduate student mentor should initiate a discussion of expectations as a member of the group. The graduate student should set clear and well-outlined expectations of the involvement of the undergraduate in the laboratory. Additionally, the graduate student should provide an outline of project aims and what the undergraduate is expected to accomplish for the project. If needed, it can be helpful to provide a syllabus which clearly outlines goals and expectations of the work [61]. Interpersonal dynamics in the group should also be discussed to better orient the undergraduate on how the group works together. This can give mentees a better understanding of what is required regarding their role in the laboratory group and how their progress is being evaluated. Once expectations are clarified, lab and safety orientation should be provided. It is important that the mentee understands standard operating procedures, personal protective equipment requirements, safety protocols, and waste management before starting hands-on work.

At the beginning of the mentee's experience, the graduate mentor should establish a well-defined direction for day-to-day activities. One of the first objectives when a new mentee is starting research is to begin technical skills training. Therefore, the graduate student needs to coordinate and pre-plan which trainings will be critical to learn at the beginning of the project. The use of an e-calendar, such as Google or Outlook, to schedule trainings or other activities is especially useful so that it can be accessed by multiple users and updated as needed (Fig. 3). When first orienting a new undergraduate, planning for the training to take at least twice as long as training a graduate student peer is a reasonable preliminary estimate. When beginning a new technical skills training, it is best practice to first use the detailed protocol prepared previously. The mentee should first read the protocol in-depth from beginning to end and ask any initial questions after reading. Once initial questions have been answered, the graduate student and mentee should talk through the protocol in detail together. When discussing the protocol, the graduate student should explain

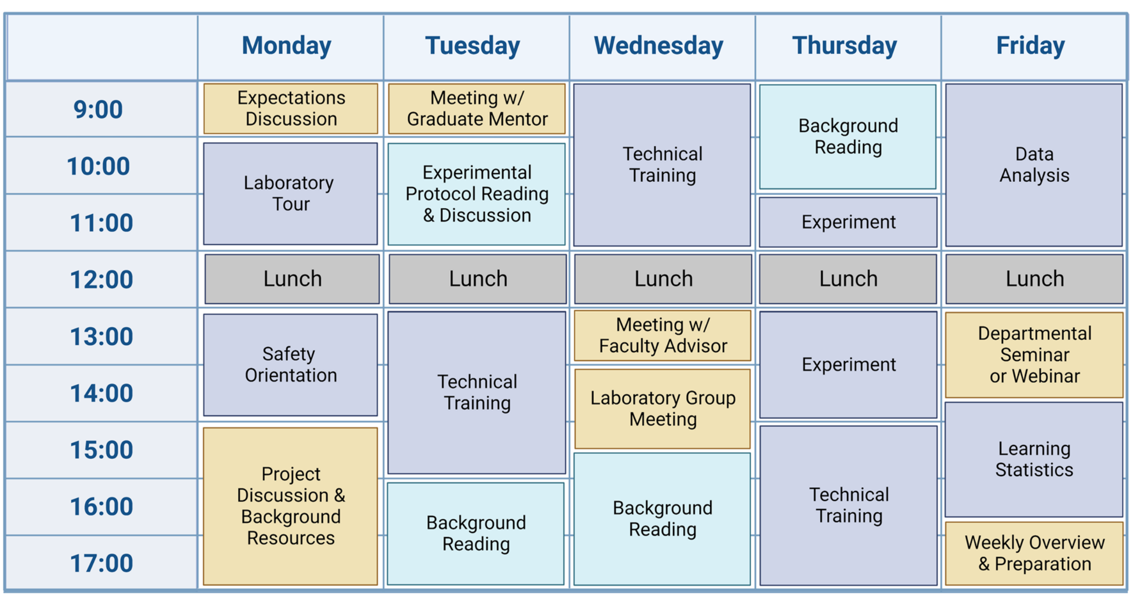

Fig. 3 E-calendar example for planning mentee's first week in the laboratory. Demonstration of the high degree of structure a novice undergraduate researcher may need when first beginning full time in the laboratory. All activities, such as meetings (orange), learning through background resources (blue), and hands-on activities (purple), should be scheduled

safety procedures and waste management, the purpose of reagents/algorithms used and why they are used at certain steps, and the reasoning behind performing steps in the order written. The undergraduate should then ask any final questions before beginning supervised, hands-on training. Training should transpire in degrees of independence. This may occur in the following order: first, the undergraduate should watch the graduate student execute the protocol, then do the protocol themselves while directly supervised, and, finally, perform the protocol alone with the graduate mentor nearby for questions or aid. However, these steps may be recurrent rather than directly in succession depending on the difficulty of the experiment and/or aptitude of the mentee. Additionally, it is important that the undergraduate is not passively following the steps of the protocol. The mentee should be able to explain what they are actively doing at each step and why each reagent, mathematical or coding function, and/or equipment is important in the experiment. Tangentially, engineering design projects should incorporate any end users, such as patients, clinicians, advocacy groups, or clientele, into the design process. By collaborating with any applicable end users, mentees can further appreciate the project's significance and incorporate universal design concepts into their project. This level of knowledge, critical thinking, and user understanding not only prepares the mentee to understand why what they are actively doing is important but also helps them to discuss, deliberate design options, and further explain their scientific results to others.

The development of independent research skills is one of the main reasons undergraduates participate in biomedical engineering research. Therefore, the solid training of research skills is essential to build the mentee's confidence and a firm scientific foundation. The moment the undergraduate enters the laboratory, proper research habits should be taught and established. Holding mentees to a high standard is essential for optimal data generation and collection, and corrections to habits should be done when needed. Graduate student mentors should continuously assess the skill level the undergraduate has by clear and observable steps. By defining the mentee's practical skill competency as either novice, intermediate, or mastery, graduate student mentors can identify weaknesses and provide feedback for improvement. This can be done through direct assessment by having the undergraduate perform clear and observable steps for individual laboratory skills, such as the accurate and precise use of a micropipette, use of a light microscope, calculation and preparation of diluted samples, sufficiently commented code, or accurate graphical data representation [62]. Indirect assessment can also be used when the practical skill is needed in a related, assessed activity [63]. When a mentee can conduct an experimental procedure flawlessly without the graduate student mentor, the technical skill is finally acquired. However, the undergraduate should not only learn technical skills but also learn how to research answers to their questions. Continuously providing answers to the mentee's questions may come at an ultimate disservice to them. To help the mentee form strong, independent research skills, they should be directed to research their questions through primary or secondary data sources and provide an explanation to the graduate student mentor [64]. By doing so for select questions, a more in-depth discussion between the two can be fostered while simultaneously building the mentee's skills and confidence.

When training a novice researcher, the graduate student should anticipate that the undergraduate will make mistakes and fail at times. Setbacks are inherent in the research process, and the graduate student should foster an environment built around psychological safety [65, 66] as well as provide the mentee with the freedom to fail. Teams working on a project or toward an overall goal inherently collaborate and learn interdependently. Researchers ask questions, seek feedback, propose new hypotheses, and report errors. How others respond can affect a person's performance and internal motivation [67]. Therefore, respectful and productive discussions centered around the accomplishments in a project or the early prevention of problems can benefit both the mentor–mentee relationship as well as the experience of the undergraduate. When errors occur, it could be the first time the undergraduate may be experiencing academic disappointment. Mitigating the fear of failure in mentees is a significant responsibility of the graduate student mentor as they actively work to enable psychological safety. When a mistake or error is made by the mentee, the graduate mentor should not take over the rest of the work. It is important that the two discuss the mistake together and plan how to avoid it in future experiments [68]. The graduate mentor should model how to overcome mistakes or setbacks in the research process and how to effectively deal with frustrations or problems pertaining to a study. Sharing a story of a time when an error was made by the graduate student is helpful for mentees to understand that research inherently comes with obstacles. Additionally, the graduate student should highlight aspects around the mistake to boost confidence in the mentee, such as the mentee actively learning a new protocol, implementing new data or statistical analyses, or having the ability to catch and own mistakes made. By having open conversations around inherent aspects of the research process, a supportive and psychologically safe environment can be maintained while allowing undergraduates to remain motivated and further comprehend research integrity [69].

Fostering Progressive Autonomy and Scientific Communication

Fostering independence and autonomy over time is crucial throughout the undergraduate research experience [70]. As a mentor, a goal is to produce a more advanced and autonomous mentee by the end of the project. When novice researchers begin, they first acquire a basic understanding of the project and its procedures. A main pitfall of undergraduate biomedical engineering research is that many mentees do not understand how their project falls within the context of a larger research picture [9]. To help resolve this common issue, the graduate mentor should continuously revisit the project background, gaps in literature knowledge, the goal of the mentee's research project, and how knowledge generated from the project can be applied in a larger context. By the end of the experience, the undergraduate should be able to place their project in the bigger picture of the graduate mentor's dissertation, laboratory goals, or societal impact. Additionally, the mentee should not only be able to deliver and quantify data from experiments, but they should also have the ability to explain the rationale behind the experiment and interpret the resulting data. As undergraduates advance further, they become more skilled in problem-solving and may be able to plan the next experimental steps. An effective graduate mentor should aim to help mentees advance from one-on-one instruction to increased ownership and relative independence over time. Over the course of the research experience, as the mentee becomes more adept and grows in degrees of independence, the mentor should shift from providing the mentee a high degree of structure and guidance to providing structured guidelines that are open to inquiry and investigation. As a result of more autonomy over the course of their project, mentees should be given escalated responsibilities, more control over their day-to-day schedule, and less oversight for experiments. Undergraduates with enhanced research and scientific understanding should be given opportunities later in the research experience to outline experimental design aspects and formulate experimental controls. This allows for the students to attain time and project management skills, project ownership, increased confidence in research abilities, and increased investment in the project. Undergraduate students in extended research experiences may also be given the opportunity to teach a technical skill to incoming graduate or undergraduate students in order to further increase their knowledge and gain skills in mentoring.

Additionally, the ability to effectively communicate scientific results and present data is an essential outcome of successful undergraduate research. A balanced scientific training will include the opportunity for the mentee to present their data throughout their experience. This can be accomplished by several means. First, after an experiment is completed, the graduate mentor may ask the mentee to explain what the data implies. This is an informal way to advance the mentee's scientific communication by fostering a conversation and demonstrating how the graduate student interprets data. Second, the mentee should be involved in laboratory meeting presentations. At the beginning of the research experience, this may comprise having the mentee present the background and rationale for the graduate student's presentation or for a related journal club article. As the project advances, the mentee should be given the opportunity to present their own data periodically. This allows them to receive constructive feedback from the entire group while improving scientific communication skills. These skills can also be promoted using written, oral, or poster formats during the experience [71]. At the end of the project, the mentee may be asked to independently lead a formal laboratory meeting and present the final results from the entire research project (more information in section "Providing Opportunities for Career Development"). The combination of increased independence and ability to effectively communicate scientific results characterizes a successful undergraduate research experience.

Providing Opportunities for Career Development

A key aspect of being an effective undergraduate mentor is to help drive the mentee toward their own professional career goals. Graduate student mentors should actively seek out networking opportunities, award nominations, professional organizations, data presentation, and other developmental occasions for their mentee in the department, university, and broader biomedical research community. Networking can occur in many forms, and developing social capital through the research group's network can benefit mentees greatly. Social capital is the resources gained through relationships, network associations, and group memberships that can help students access opportunities [48]. The use of personal contacts and embedded resources can affect professional career outcomes, give a competitive advantage, and allow the undergraduate to attain greater social status and mobility within the scientific community [72, 73]. Different resources can be attained by the undergraduate mentee based on the available network of members within the mentoring triad [11]. Acting as a link in the undergraduate's networking sphere, the graduate student should introduce the mentee to others they may not directly interact with, especially if the mentee is interested in a particular research area. A simple way to expand the mentee's university network is to invite them to sit in on meetings. Here, they can be introduced to others within the graduate student's sphere naturally, while simultaneously participate in research discussions. Expanding the mentee's network is of utmost importance and a good investment as the access to multiple mentors and role models can provide additional support and guidance [74–76]. The graduate student should promote the mentee among colleagues and network on their behalf even when the mentee is physically absent. Additionally, access to the faculty advisor's social capital can provide further opportunities for educational support, referrals, and letters of recommendation [77, 78]. Investment in developing an undergraduate's connections through the research group's social capital can provide access new, otherwise largely unattainable, opportunities to expand their participation in the field of biomedical engineering.

Mentees should also be provided opportunities to broaden their scope and develop their own research interests. Sending undergraduates to departmental seminars, research symposiums and webinars, or other academic events exposes them to new knowledge, research fields, and techniques. In addition, if the undergraduate voices their interest in either a certain technique not used in their current lab or interest in a different research field, graduate mentors should find peers or other undergraduates in research for their mentee to shadow. If the interest lies outside of the graduate student's direct networking sphere, the faculty advisor is also an exceptional resource to make introductions. The graduate student mentor should also submit award nominations for their mentee's research findings, which can be found within biomedical engineering departments, the university, or through professional engineering societies. By nominating an undergraduate for a research award, the laboratory group is acknowledging their efforts, achievements, and successes. Lastly, the mentee should be given opportunities to disseminate their research findings. This may look as simple as leading a laboratory meeting, co-author a publication if sufficient contributions were met, or presenting a poster at the university level or at a national conference [79]. Ideally, undergraduates should be given opportunities to attend local or national conferences to further their professional development. Groups may arrange for mentees to present research findings at national conferences, such as the Biomedical Engineering Society (BMES) Annual Meeting or the National Diversity in STEM conference (NDiSTEM) hosted by the Society for Advancement of Chicanos/Hispanics & Native Americans in Science (SACNAS). Mentees interested in the pursuit of advanced training and careers in biomedical and behavior sciences may also consider attending the Annual Biomedical Research Conference for Minoritized Scientists (ABRCMS). For those interested in pursuing careers in industry, CareerCon hosted by SACNAS may be of interest. By arranging for undergraduates to participate in biomedical engineering conferences intended for their professional development, the laboratory group can promote and foster the individual professional career aspirations of each mentee.

Future Direction for Mentorship Development and Research

The majority of literature regarding undergraduate research is focused predominantly on faculty practices and undergraduate student outcomes. However, undergraduates primarily interact directly with graduate students, who also provide mentorship and supervision. This relationship is considered less in literature, and additional resources to improve the development of graduate students as effective mentors are needed. More work dedicated to identifying, analyzing, and responding to the needs of graduate students in undergraduate research mentorship should be supported by biomedical engineering graduate programs and research institutions [15]. Surveys of both graduate student mentors and undergraduate mentees before and after the training period can assess both skills development and confidence in research and mentoring. Mentorship skills, philosophy, and outcomes of the graduate student themselves should be evaluated. By examining practices implemented by graduate students, training programs or materials for undergraduate research mentorship can be curated more specifically for postgraduates. For example, a study identified the critical components of cognitive apprenticeship practices that were actively applied by postgraduate mentors in the various stages of undergraduate research mentoring [80]. Additionally, institutions and programs should consistently both evaluate graduate students' effectiveness as a primary mentor on undergraduate outcomes through surveys and reward those who are successful with institutional mentorship awards. Support for graduate student mentors should be provided through the implementation of formal mentorship training specific to these early career researchers who are novice mentors [81]. Formal mentoring courses should focus on building skills and developing identities as a mentor. One such program is *Entering Mentoring* [82], which was developed by the Center for the Improvement of Mentored Experiences in Research (CIMER, Table 2) at the University of Wisconsin–Madison. This evidence-based training program was developed for research trainee mentors at varying career stages. Many research universities offer the formal, 10-week long course for graduate students. Other undergraduate universities have integrated the *Entering Mentoring* curriculum with an undergraduate course to help graduate students practice mentoring in a supported and structured environment [83]. In addition to a formal training course, the establishment of peer discussion groups could aid in graduate students sharing teaching methods and strategies among one another. The facilitation of professional development and structured opportunities is needed in order to intentionally increase the impact of undergraduate research experiences within the biomedical engineering field.

Conclusion

As undergraduate involvement in biomedical engineering research continues to increase, their presence and work have become integral to many research groups and the broader

Table 2 Resources for undergraduate learning

Category	Description of key concepts	References
Presentations	Basic guideline that outlines preparation, structure, content to include, and use of visual aids in a formal presentation	[95]
	Evidence-based practices to strategically design conference presentations that will engage audiences and gather constructive feedback	[96]
Introduction to R & statistics	Step-by-step resources covering installation of R and RStudio, R syntax and programming fundamentals, data wrangling and visualization, and basic statistics	[97, 98]
Conference abstracts	Discussion of steps and suggestions for the preparation and submission of an abstract for national conferences with annotated examples	[99]
Poster preparation & presentation	Walk through of an academic poster's purpose, design and formatting, and content to include with schematic examples and details. Also discussed are how poster sessions operate and tips on poster presentation	[100–103]
Manuscript preparation	Break down of the structure of a manuscript, elements to include in main sections, quality checklists, how to cite literature sources, recommendations for common pitfalls, and tips on how to avoid plagiarism	[104–106]
Assessments	Survey used to evaluate undergraduate research experiences on a scale of 1–5 for gains made in areas, such as scientific thinking, personal gains, technical skills, and scientific community	[107]

community. Undergraduate researchers are passionate and hands-on in the laboratories, bringing initiative, creativity, and novelty to projects. Working one-on-one with these early career researchers is an exciting and rewarding opportunity for graduate students as they help shape the scientist the undergraduate mentee becomes. However, undergraduate research mentorship can also be a daunting transition for graduate students when first navigating this new supervisory role. The act of mentorship requires significant consideration and demands time, continuous attention, and consistent reforming of personal pedagogy. Therefore, this article aims to discuss the implementation of applicable methods and practices for mentoring biomedical engineering undergraduate researchers to support the development of effective graduate student mentors and undergraduate research success. While acting as an effective mentor may never be an easy task, it will most likely remain a predominant part of biomedical engineering graduate education. Continuous advice and education surrounding research mentorship should be offered within the biomedical engineering community to support undergraduate learning and outcomes (Table 2). The initial guidelines, recommendations, and resources within this article are designed as a reference to aid graduate students to develop into effective undergraduate research mentors and should be further tailored to the individuals within the mentorship triad.

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