Methods in Physiology
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Harry J. Witchel
Michael W. Lee *Editors*

Technologies in Biomedical and Life Sciences Education

Approaches and Evidence of Efficacy for Learning

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Editors
Harry J. Witchel
Department of Neuroscience
Brighton and Sussex Medical School
Brighton, UK

Michael W. Lee
Department of Medical Education
Geisel School of Medicine, Dartmouth College
Hanover, NH, USA

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Foreword

The idea for this book was born at Physiology 2019, The Physiological Society's annual meeting in Aberdeen, Scotland, when I heard Harry Witchel speak on "A video on the pathophysiology of heart failure for reinforcing first year medical students' learning: do video techniques that break from medical education tradition undermine the video?" The meeting included many other talks and posters on technology for teaching, ranging from virtual and paperless laboratory practical teaching to gamification, patient simulation, 3D printing, and augmented reality. As I talked with presenters, a question came to mind: what do we know about how well these technologies work?

It has taken years for the higher education community to adopt active learning strategies, with many teachers asking "where is the evidence that active learning is better than what we have always done?" It was not until Scott Freeman and collaborators published their meta-analysis (Freeman et al. 2014) showing learning gains with student-centered teaching that active learning began to infiltrate classrooms more widely. But at the same time, educators everywhere were rapidly adopting new technologies for teaching, without questioning their role in the curriculum and whether these technologies improve student learning and outcomes. How do we know that using technology is not doing our students a disservice by making them too dependent on the technology and unable to function adequately without it? What do we know about how these technologies foster or undermine desired skills and behaviors in addition to teaching content? How can we use technology best to improve learning and enhance student outcomes?

When Harry Witchel and Michael Lee agreed to take on the challenge of finding experts to address some of these questions, it was 2019, and we had no idea that a global pandemic of SARS-CoV-2 was about to disrupt everything we do in higher education. Technology that had been a novelty in education suddenly became essential—the only way we could teach. As a result, the evidence for advantages and disadvantages of educational technology in chapters that follow is more timely than ever. We hope that you enjoy exploring these essays on *Technologies in Biomedical and Life Sciences Education*.

University of Texas at Austin, Austin, TX, USA Dee U. Silverthorn

American Physiological Society eBook Committee, Rockville, MD, USA

America Physiological Society (2022), Rockville, MD, USA

Reference

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, *111*(23), 8410–8415. https://doi.org/10.1073/pnas.1319030111.

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—Harry J. Witchel, Ph.D.

To my wife Ernestine, my daughter Sofia, and my son Benjamin, thanks for enduring countless nights of me writing, in a never-ending stream, on my laptop alternating between exhilaration and depression over the course of these past 2 years. In words of Gene Fowler, “writing is easy, all you do is sit staring at a blank sheet of paper until drops of blood form on your forehead.” A deep thanks to my friend and colleague Andy Butler (may another ACL be in our future); to my best friend JKZ for constantly listening to me talk about this project, incessantly and without context at times; to the APS Book Committee and to Springer, specifically Srinivasan Manavalan and Markus Späth; and to fate (specifically DUS) for providing me the opportunity of meeting and working to Dr. Harry Witchel. Not only has he been an outstanding co-editor, who has been consistently inspiring and intellectually challenging, he is the only person on the planet I can truly talk to about fonts (he genuinely laughed when I bid him “font regards”). Those conversations are only beginning. I am privileged to emerge from this project with both a colleague and a friend in Harry.

—Michael W. Lee, Ph.D.

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Editors and Contributors

About the Editors

Harry J. Witchel is a discipline leader in physiology on the University of Sussex site of Brighton and Sussex Medical School (UK). His team's interdisciplinary research within the Department of Neuroscience resulted in his students winning the Best Research Paper Award at the international ECCE conference (2019); he also researches and innovates on educational topics revolving around human computer interaction and assessment. He has received over 15 teaching awards and recognitions, including three at the national level: from the British Science Association, the Physiological Society, and most recently a National Teaching Fellowship from Advance HE (2021). He is a long-standing member of the Physiological Society, where he currently serves on the Education, Public Engagement, and Policy Committee. His teaching qualification is as a senior fellow (Higher Education Academy); he received his A.B. (college) in biophysics from Columbia University (New York) and his Ph.D. from the Department of Physiology-Anatomy at the University of California at Berkeley.

Michael W. Lee received his masters' and doctoral degrees in medical science, with a focus on medical pharmacology, from the Morsani College of Medicine at the University of South Florida. This was followed by a postdoctoral fellowship at the University of Florida College of Medicine at the Shands Cancer Center. He has served as a founding faculty member at several pharmacy and medical schools where he has trained students both in the classroom and in the laboratory. He is currently an associate professor at the University of Texas at Austin Dell Medical School in departments of medical education and oncology. He is also an associate member at the Livestrong Cancer Institutes. His research interests center around delineating molecular mechanisms of therapeutic agents for cancer and on development of novel educational technology tools for enhancing basic science learning. He has received numerous awards for teaching including a Golden Apple (2011) and a Recognition of Innovation award (2011), and he has been awarded excellence in teaching awards 3 consecutive years (2019, 2020, and 2021). He received a Teaching Career Enhancement Award from the American Physiological Society in 2018. In 2020, he was awarded the designation of Distinguished Teaching Professor, following admittance into the University of Texas at Austin Dell Medical School Academy of Distinguished Educators. Most recently he was admitted to the University of Texas System Kenneth I. Shine Academy of Health Science Education in recognition for teaching and educational research excellence. He is an active member of the International Association of Medical Science Educators (IAMSE) and the American Physiological Society (APS), and he serves on the editorial board of the journals *Pharmacology Research and Perspectives, Kidney and Blood Pressure Research, and Frontiers in Pharmacology*.

Contributors

Peter Alston BPP Education Group, Manchester, UK

Sandra Arango-Caro Donald Danforth Plant Science Center, Saint Louis, MO, USA

John Barrow University of Aberdeen, Aberdeen, Scotland, UK

Cynthia Brame Vanderbilt University, Nashville, TN, USA

Andrew C. Butler Washington University in St. Louis, Saint Louis, MO, USA

Kristine Callis-Duehl Donald Danforth Plant Science Center and Saint Louis University, Saint Louis, MO, USA

Duncan Cole School of Medicine, Cardiff University, Cardiff, Wales, UK

Melanie M. Cooper Michigan State University, East Lansing, Mi, USA

Bryan Dewsbury Florida International University, Miami, FL, USA

Sheila A. Doggrell Queensland University of Technology, Brisbane, Australia

Renée M. Filius Utrecht University, Utrecht, The Netherlands

Daniel Franceschini College of Medicine, University of Central Florida, Orlando, FL, USA

Terry Gleave University of Liverpool, Liverpool, UK

Richard Guy Victoria University, Melbourne, Australia

Heeyoung Han School of Medicine, Southern Illinois University, Springfield, IL, USA

David M. Harris College of Medicine, University of Central Florida, Orlando, FL, USA

Mark Hirst The Open University, Milton Keynes, UK

Ihuoma (Yvette) Igbokwe School of Medicine, Southern Illinois University, Springfield, IL, USA

Victoria Jacoby UCLA David Geffen School of Medicine, University of California, Los Angeles, CA, USA

Christine A. Kauffman College of Medicine, University of Central Florida, Orlando, FL, USA

Philip J. Kellman UCLA David Geffen School of Medicine, University of California, Los Angeles, CA, USA

Rudi Klein Victoria University, Melbourne, Australia

Michael W. Klymkowsky University of Colorado Boulder, Boulder, CO, USA

Sally Krasne UCLA David Geffen School of Medicine, University of California, Los Angeles, CA, USA

Kenneth Langlands University of Wolverhampton, Wolverhampton, UK

Michael W. Lee Department of Medical Education, Geisel School of Medicine, Dartmouth College, Hanover, NH, USA

Kristina Lisk University of Toronto, Toronto, Ontario, Canada

Hilary MacQueen The Open University, Milton Keynes, UK

Christine Massey UCLA David Geffen School of Medicine, University of California, Los Angeles, CA, USA

John C. McLachlan University of Central Lancashire, Preston, UK

Maria Mosley School of Medicine, Southern Illinois University, Springfield, IL, USA

Maria Mylopoulos University of Toronto, Toronto, Ontario, Canada

Izabella Penier University of Central Lancashire, Preston, UK

Joseph Rathner University of Melbourne, Melbourne, Australia

Emma Rengasamy Department of Public Health and Primary Care, University of Cambridge, Cambridge, UK

Louise Robson University of Sheffield, Sheffield, UK

Puspha Sinnayah Victoria University, Melbourne, Australia

Cynthia Taylor University of Rhode Island, Kingston, RI, USA

Shelley Tischkau School of Medicine, Southern Illinois University, Springfield, IL, USA

Christopher Torrens Royal College of Surgeons, Dublin, Ireland

Sabine G. Uijl Utrecht University, Utrecht, The Netherlands

Lisa L. Walsh Donald Danforth Plant Science Center and Saint Louis University, Saint Louis, MO, USA

Emma R. Wester Donald Danforth Plant Science Center and Saint Louis University, Saint Louis, MO, USA

Harry J. Witchel Department of Neuroscience, Brighton and Sussex Medical School, Brighton, UK

Nicole N. Woods University of Toronto, Toronto, Ontario, Canada

Part I
Introduction and Educational Context

Chapter 1
Introduction: Intentional Innovation in Educational Technology and Media to Promote Students' Holistic Development

Michael W. Lee and Harry J. Witchel

The future is already here—it's just not very evenly distributed.

– William Gibson (Neuromancer, 1984)

Abstract This chapter introduces the book *Technologies in Biomedical and Life Sciences Education*. In addition to providing the précis for the other chapters of the book, it contextualizes those chapters by addressing how far technology has taken bioscience education and also speculating on where technology needs to go. Technology, particularly in conjunction with innovations in pedagogy, has profoundly influenced the experience of teaching and learning science, and examples are provided, some familiar (e.g., video lectures in flipped classroom) and some emerging. Compared to the experience, the striking outcomes of past innovations in technology and pedagogy have been more weighted toward inclusivity, opportunities, and participation rates. For the future, we propose an intentional development of educational technology and media that supports holistic development of students. This goes beyond design-centered or market-driven research and focuses on student competencies and skills known to play a role in learning and professional skills attainment. These include social, metacognitive, and noncognitive competencies, such as teamwork skills, social behaviors, empathy, and emotional regulation. The challenge is to use intentional innovation to achieve student learning of competencies, by leveraging what computers are particularly good at: timing, repetition, and vigilance. The expected result will probably involve learning with repetition, deeper learning with models, collaborative and cooperative learning, and self-regulated learning. We engage in serious discussion

M. W. Lee (✉)
Department of Medical Education, Geisel School of Medicine, Dartmouth College, Hanover, NH, USA
e-mail: Michael.W.Lee@dartmouth.edu

H. J. Witchel (✉)
Department of Neuroscience, Brighton and Sussex Medical School, Brighton, UK
e-mail: h.witchel@bsms.ac.uk

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on the challenges and obstacles inherent in refocusing media creation and educational technology innovation. We close with an overarching summary of the different chapters and how they fit together into this cohesive narrative.

1.1 Education Technology in the Biosciences: Practical Issues and a Research Problem

When considering a pedagogical method designed to convey knowledge to a learner, both instructors and students should ask two questions: (1) Will the students use it, and (2) does it actually promote learning and development? This book focuses on both, and neither question is trivial. The question of whether students engage with a tool or pedagogy segues immediately to another question: Which students? This leads to serious inquiries about inclusivity and equity. The question of efficacy and efficiency raises even more issues. How and why does it work? We need to understand mechanisms to know: Are all the steps in the pedagogical process necessary for it to be successful? Can it survive being stripped down? These are the kinds of practical questions that serious instructors, faculty leaders, and educational researchers need to consider. The chapters in this book critically examine teaching methods, innovative technologies, and controversial issues in bioscience education that have reshaped and reimagined a student's higher-education experience over the past 10 years.

Although this book is about the plethora of new educational technologies now available for teaching and learning, this is not a book of recipes, nor is it an advertisement for some innovative methods. This book was commissioned to (1) prompt transformative research by (2) engendering extensive critical discussion. This critical approach is needed because some new teaching processes are fads that may not have significant effect on learning (Natividad et al., 2018; Spector, 2020). Indeed, the long-term impact of using educational technologies to enhance student learning remains an ongoing subject of research (Spector, 2020). As educators we wanted to read critically about the evidence for the range of technology-supported techniques in a synoptic way. As editors, we commissioned our authors to produce such an overview, so that, for your own students, you can best decide which techniques are reliable and worth exploring. The chapters in this book address the latest research on efficacy of the most relevant and practical educational technologies and advances. Some controversial issues that we wanted to see explained are also included, and ultimately the book raises serious questions about our values. If you skim through the various chapter abstracts, you will see that the different chapter authors definitely do not trivially agree with one another. Tough questions are asked in a chapter on cheating and in a debate on whether students still need to attend classroom lectures in an era of recorded lectures. The assembled chapters provide a nuanced consideration of what researchers should be researching by asking experts what they are currently speculating about. We believe that this approach will provide an important point of departure for future research, and we are sure that it will be an excellent addition to the discourse.

This chapter will contextualize the rest of the book as a call to action for how education researchers are critical for designing the future of education, and consequently the future of society. In addition to outlining the other chapters of the book, this chapter will situate those chapters as part of the educational movement toward valuing and including intention as well as innovation, competencies as well as knowledge, and noncognitive as well as cognitive skills. Our goal is not only to have smarter students but also to have more inclusive and well-developed students that we will want to work among in the future.

1.2 The Intentional Development of Technology in Teaching and Learning of Bioscience

1.2.1 The Impact of Computers and Educational Technology on Cognitive Processes

When thinking about the approach of developing and deploying educational technology to improve student learning, a quote attributed to Steve Jobs comes to mind:

> Some people say, give the customers what they want. But that's not my approach. Our job is to figure out what they're going to want before they do. People don't know what they want until you show it to them. That's why I never rely on market research. Our task is to read things that are not yet on the page. (Isaacson, 2011)

This design-centered approach that consumer technology companies employ seems to be the pattern that education companies and academic institutions follow in regard to learning and educational technology. Conceive of a tool or technology you think students and instructors will want or may find useful, produce a product, and sell it to schools and students as something they will want, even though it has not been proven to be beneficial. This approach may work well as a business model for consumer products, but a new educational technology may not necessarily benefit the students' learning when developed in this manner (see Chap. 14 on social media). Although it screams innovation, this may not be the best approach for advancing learning and skills attainment. Alternatively, many technology companies conduct market research and use customer (i.e., students and faculty) input to guide innovation and product creation. This approach is helpful so long as instructors and students think long and hard about what the real barriers are to learning and whether or not these issues can even be solved with technology. Yet, in the case of learning, as opposed to producing a new phone or smart car, we are talking about functional benefits here rather than simple aesthetics or convenience. Learning and educational technology should be supported by evidence and grounded educational research that drives improvements in knowledge attainment, retainment, or application. The goal should be student development.

1.2.1.1 Technology Is Not Solely the Answer

In 1966, the architect Cedric Price made the provocation, “Technology is the answer, but what was the question?” The belief that science and technology is always the best way to solve everything—and that it *will* solve everything—is sometimes called technological solutionism, while critics in the humanities and social sciences have labeled it scientism; Chap. 2 (inclusivity) pleads a strong case that educators, and their financial managers should not blindly follow technological innovations without question or nuance; those who do may find themselves in the kind of ethical cul-de-sac in which science found itself during the first half of the twentieth century. Ethical contemporary scientists must learn the lessons from the enabling roles played by early scientists in eugenics, weapons of mass destruction, and fascist regimes. For educators, this means that cultural progress in our institutions is at least as important as technology. Chapter 9 on qualitative feedback also strongly argues that the relational elements of education (e.g., student-faculty research projects) are better at teaching than the transactional elements; there are more meaningful ways of teaching than “I give you a test, you give me your answers, I give you a mark.” These kinds of status-based hierarchies are openly questioned in Chap. 3 (empowering students as partners), which suggests that we as academics can empower students in their own learning, so long as we are prepared to trust our students enough to relinquish some of our control. Whereas authoritarians have long used technology to control others, Chap. 3 suggests ways that we can use educational technology to provide students with a greater degree of self-determination.

As we see in the chapters of this book, in many cases (with some notable exceptions) the barriers to learning and mastery are more about the receptiveness of the learner to engaging with the material, rather than the media via which the information or skills are conveyed (Clark, 1983; Kozma, 1994). Thus, technology is not always the answer, particularly when the right question may not have even been properly formulated. Indeed, learners learn best when they are struggling and questioning their own knowledge (Bjork et al., 2013). The question may be the following: Are there technologies that can increase student engagement with the process of struggling to learn? We need tools and activities that enhance engagement and are satisfying for students (e.g., gamification or personalization) while also driving learning gains. Thus, the driving vision of educational technology development should not *only* be market research or some prescient vision of what people want. Rather, educational research that reveals how each student learns best, so learning can be individualized and inclusive, should be a driving force behind educational technology innovation. This way, the decision can be made as to whether or not a high-tech solution needs to be leveraged (or created), especially if a low-tech option exists and can be used instead. This is not to say that technological improvements for the sake of change should *not* be undertaken. Oftentimes, the “design-thinking” technological solution can in fact make tools that drive knowledge or skills attainment more accessible, more visually appealing, sometimes in a more cost-effective manner. However, from an educator’s perspective, rather than prioritizing product development for profit's sake and user satisfaction, innovation in an educational space needs to be carefully, deliberately, and intentionally thought out in a way that is backed by classroom research. Thus, tools that actually advance learning and address classroom needs can be prioritized over simple technological flashiness that may not align with research findings.

1.2.1.2 How Students Learn with Technology Is the Answer

At the center of the issue of using technology to drive learning is recognizing what computers are actually good at and matching it with the educational need. According to the 2018 consensus study report by the US National Academy of Sciences "How People Learn II" (National Academies of Sciences, Engineering, and Medicine, 2018), the advantages information conveyed by learning technology include:

- **Learning through repetition**, which can be easily automated and tracked with learning technology
- **Deeper learning with models**, both via use of intelligent tutor systems and construction of model systems
- **Collaborative and cooperative learning**, driven by the ability to work on assignments and programs together and simultaneously
- **Self-regulated learning**, as a consequence of having the ability to test one's thinking and mental models

Educators need to go beyond learning through repetition. Yes, computers are very good at reproducibly eliciting and tracking user actions and interactions (i.e., they are better than human beings at timing, repetition, and vigilance). However, we need new ways of applying educational technologies that can harness both what we know about human learning while also incorporating the strengths of computers. These new methods should do more than simply encourage factual recall; they should lead to the holistic evolution our students need to undergo in order to personify their professional identities and competencies in the future. These include improved information transfer, the ability to work in teams, development of empathy, and skills acquisition.

As we will see in the chapters that lay ahead, there are a number of existing and emerging technological approaches that rely on learning theory and empirically derived data intentionally designed to improve thinking skills, as well as drive attainment and retention of knowledge. For example, educational technology that incorporates adaptive learning and games (see Chap. 5) allows students to enter into learning at an individual level, which permits personalization of learning. Much of this technology incorporates retrieval practice to improve long-term retention of knowledge (see Chap. 4); psychology has shown that the timing of learning reinforcement determines the biology of neuronal synapse formation, yet traditional education is mass produced with students being taught and tested in lockstep (Ebbinghaus, 1913; Kelley & Whatson, 2013; Korte & Schmitz, 2016). Fortunately, there are testing platforms that take advantage of this well-established psychology

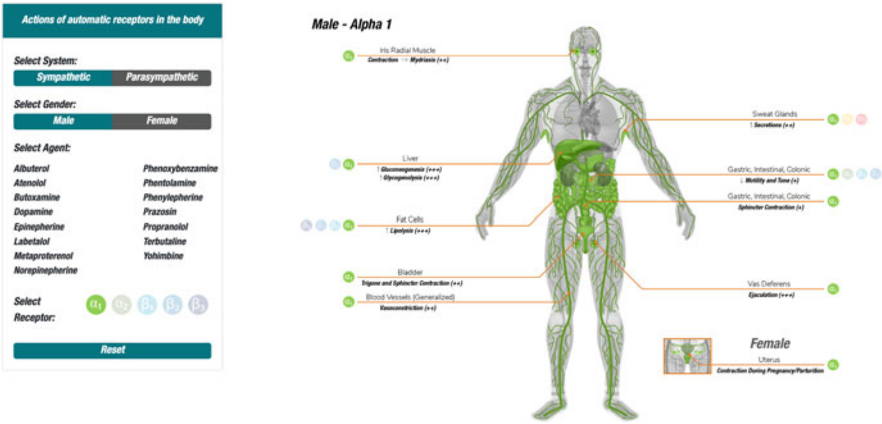

Fig. 1.1 The Integrated Pharmacology Atlas©. An electronic tool to help students visualize and interact with the autonomic nervous system anatomy, physiology, and pharmacology. Image courtesy of Michael W. Lee, Ph.D

phenomenon. Other approaches are also being developed to elicit students' deeper thinking and elaborate on their true understanding of a concept. As discussed in Chap. 8, beSocratic is an example of an assessment program that requires students to articulate their thinking rather than simply picking a single best answer choice in a multiple-choice question (MCQ).

Another example of using technology designed to improve cognition is leveraging the superior visualization and animation that computers offer. This allows developers and instructors to reimagine how complex information can be visualized and learned. The Integrated Pharmacology Atlas (Lee & Zahedivash, 2021) is an example of one such tool. Here information about autonomic nervous system anatomy, physiology, and pharmacology is linked together in the context of a virtual human (Fig. 1.1) (Zahedivash & Lee, 2018).

This format allows students to interact with the different autonomic receptors to learn their location, function, and how drugs can alter function both therapeutically and adversely at offsite receptors. Because the autonomic receptors are presented in their natural organ ecosystems in the human body and students can interact with the receptors and see their function, the barrier for entry into this complex domain of biology is reduced. This is an application where digital technology drives a student's initial learning by providing them with a more intuitive organizational model that they can interact with and manipulate.

In a related example, educational technology can also be designed to enhance engagement when paired with non-technology-based pedagogies like problem-based learning (PBL) by reframing how case information is presented to students. Creation and implementation of educational electronic health records (EHR) programs early in a curriculum to present clinical cases helps students contextualize knowledge and get acclimated to the manner in which these cases

Fig. 1.2 Educational electronic health records (EHR) paired with small group activities. Media and educational technology can be used to organize, focus, and augment basic science learning in a clinical, patient-centered context. Image courtesy of Michael W. Lee, Ph.D

are encountered in clinical practice. Pairing educational EHR programs with PBL, for example, can lead to rich, structured learning events, where students discuss basic science content in the context of a patient (Fig. 1.2) (Steinel et al., 2019).

The common thread linking these tools is that they encourage students to interact with knowledge rather than simply being passive receptacles receiving knowledge from a resource.

1.2.2 Impact of Computers and Educational Technology on Noncognitive Processes

There is a documented need for strong noncognitive attributes, such teamwork skills, social behaviors, empathy, emotional regulation, and professionalism (among others), due to the professional nature of health- and science-related careers (Bennett & Gadlin, 2012; Chakraborti et al., 2008; Martin & Ochsner, 2016; McNair et al., 2005; O'Connell & Pascoe, 2004; Ritter et al., 2017). Furthermore, there appears to be a relationship between noncognitive attributes and assessment performance, such that performance can be enhanced with teamwork and active learning (Adam et al., 2012; Beckerson et al., 2020). Therefore, finding ways to cultivate noncognitive attributes and skills is a priority as students' progress in their professional training. In contrast to cognitive ability, these attributes are more difficult to teach and measure. While it remains unclear how well computers and technology can be used to teach or improve these noncognitive skills in a temporally durable manner, there are some promising approaches that merit further investigation, which are discussed in the following sections.

1.2.2.1 Teamwork Skills and Social Behaviors: The Influence of Communication Using Social Media Technology

The capability of computers and technology to facilitate communication provides an avenue to influence students' noncognitive skills. Good communication between students can improve engagement and enhance socialization, which may lead to learning gains (Goldman & Wong, 2020; Luiz Adrian et al., 2015). Communication is also a product of teamwork training and experiences (Bennett & Gadlin, 2012; Chakraborti et al., 2008; O'Connell & Pascoe, 2004). While technology has the potential to improve communication in ways that can enhance teaching and learning, these tools also come with some notable liabilities that need to be carefully considered ahead of time. The challenge then is to leverage technology and media in ways that favor group activities, teamwork, collaboration, and disincentivize isolation and disengagement that can accompany the use of technology, so that students' noncognitive growth flourishes.

As discussed in later chapters of this text, there are a number of Web-based tools that can be employed to facilitate communication between students to enhance learning. Social media stands out among available forms of technology-based communication tools because of its widespread use and the native familiarity students have with it. As Rengasamy et al. discuss in Chap. 14, social media, if used appropriately, is a powerful means to link students together and foster communication, so long as students have access to a Wi-Fi-enabled device (Chap. 2). However, they stress that it is critical to set expectations on the use of social media ahead of time to ensure professional and respectful communication. This is because, like older methods of technology-based communication, such as email, messages can accumulate so quickly that they can be missed (or even ignored), leading to professionalism issues related to timeliness, participation, and completion of assignments, for example. Likewise, electronic "real-time" social media tools like Facebook or Twitter are often rife with incorrect, or even harmful, information and messaging that can lead to confusion, de-motivating students. This in part stems from the crowd sourced aspects of social media platforms and the disconnected nature inherent in virtual communication. Consequently, rapid and more readily accessible routes of communication may actually elicit socially aberrant behavior and unprofessional actions.

Similar maladaptive noncognitive phenomena are also seen with Web-based media sharing sites used to communicate information to students. Video-based Web sites, like YouTube and Vimeo, that are often used in structured science curricula contain social media communication abilities, and students are able to comment on videos, sometimes unprofessionally. In addition, these venues are also host to erroneous and unprofessional content, which is often not vetted or supervised by content experts or instructors. To address these issues, whether with social media or media-based Web sites, providing guidance and expectations of student behavior and outcomes around their use and acceptable communication is clearly key (see Chaps. 7 and 14). So too is role modeling professional behavior through explicit instruction and feedback. This can also be achieved with instructor-created or instructor-curated videos or media content.

Examples of technology that bring together the positive aspects of social media-like communication with sanctioned content and faculty supervision are now beginning to emerge. For example, Perusall® is a simple but apt example of how technology can be used to enhance communication among students in the form of textbook annotations (Miller et al., 2018). In the Perusall® tool, students access reading material in digital form (e.g., a textbook, instructor developed material, PDFs, etc.) and are able to engage in a social media discussion with other students as they progress through the text, leaving comments and responses for each other. In this way, students are able to learn new material and resolve misunderstandings in real time or near real time from their peers (www.Perusall.com). This facilitates communication and teamwork among students. It may also be a means to teach professionalism as well, since it has the features of a social media tool in an academic environment and the comments can be viewed by others including the instructor. In theory, a tool like this that puts social media components in a professional context with accountability (more on this below) within a course has the potential to improve noncognitive attributes and interactions, but more research is needed to determine whether this is actually occurring. Tools like this can also be paired with active learning pedagogies such as flipped classroom.

1.2.2.2 Emotional Regulation, Empathy, and Professionalism: A Role for Instructor-Guided Technology and Activities

Technology such as simulation has been used to teach both basic science knowledge as well as procedural skills in a variety of science and health science disciplines (Klein, 2020). It may also facilitate improvements in noncognitive skills such as empathy and emotional connection of individuals in certain contexts (Harris et al., 2015; Reinemann et al., 2015). Using simulation to mimic real-life exercises, where the actions of a learner can impact the health of a simulated patient, has been shown to influence students' emotional connections to the patient (see Chap. 16) (Bearman et al., 2015). In many programs, the simulation exercise is paired with a debrief, where students gather together after the simulation to discuss the experience (Fanning & Gaba, 2007). This can provide a venue for students to form normed behaviors as they interact with other groups of students and faculty and discuss the patient, their responses, and team members actions during the simulation. Using simulation together with debrief sessions can also be used to improve professionalism that is backed up by learning theory (Corliss & Lee, 2021; Lee, 2016).

Instructors and teachers can also help students develop noncognitive skills through role modeling and direct instruction. In Chap. 9, Uijl et al. weigh the merits and challenges of delivering feedback to students via audio or video formats. In this case the feedback is offered in a one-way manner for the student to consume. However, students often respond very positively to video feedback because it is personalized and relational. For it to be successful though, one-way communication requires a culture of feedback. If paired thoughtfully with active learning exercises or self-regulated learning (SRL) approaches, this technology-mediated feedback could lead to more efficient learning.

Finally, technologies and media should also be used to reassure students on the purpose of a chosen pedagogy or activity. The dramatic surge in the use of active learning and SRL approaches in the classroom has enhanced student responsibility, which can cause stress, and it has also led students to question the purposes of learning activities. Frequently, instructors think that they have explained the purpose of using a pedagogy to deliver a topic clearly, when in fact to some students, it may not be clear at all. For example, Owens et al. found that getting students to approach discussion in a scientific manner using an active learning approach was often met with resistance because students did not see the purpose (Owens et al., 2020). Silverthorn (2020) recommends that instructors explain the rationale for active learning *repeatedly* to enhance student acceptance of active teaching approaches (Silverthorn, 2020). Frequently, our own perceptions about how we learn best and what constitutes good learning are skewed from reality (Bjork et al., 2013; Deslauriers et al., 2019). Clearly communicating with students and briefly describing the underlying learning theory and sharing data on the effectiveness of the pedagogy (technology or otherwise) may help to increase buy-in from the students and may increase compliance and engagement.

1.2.2.3 Impact of Computers on Metacognition and Self-Regulated Learning

Finally, given how important learner characteristics (e.g., engagement, motivation, and self-efficacy) are in the mastery of material, it bears consideration as to whether technology can help students develop these characteristics by influencing self-regulation and metacognition. Metacognition is defined as "the ability to monitor and regulate one's own cognitive processes and to consciously regulate behavior, including affective behavior" (National Academies of Sciences, Engineering, and Medicine, 2018). A student's emotional state as well as their belief that they can accomplish a task (self-efficacy) can both influence metacognition and, in turn, academic performance (Artino et al., 2010). Thus, in many ways educational technology and computers are well positioned to help students build or strengthen metacognition by promoting self-regulation in learning (National Academies of Sciences, Engineering, and Medicine, 2018). However, designing educational technology with the intention to drive attainment of these attributes may be the critical key to success. Educational technology, media, or Web-based tools that intentionally prompt students to think about how they are learning, such as having them articulate how and why they come up with an answer, can *directly* improve metacognition and self-regulated learning (National Academies of Sciences, Engineering, and

Medicine, 2018). Properly structured media and educational technology can help students do this (Badger et al., 2019). However, students still need to believe that the endpoints of studying are valuable and justify the personal (as well as financial) investment. Simply getting students to think and verbalize their thinking is not enough; their emotions associated with achievement are also important in determining outcomes as well (Pekrun et al., 2007). Artino et al. show that task value (how interesting, important, or useful a task is) is positively associated with enjoyment and negatively associated with emotions like boredom, whereas self-efficacy is negatively associated with anxiety (Artino et al., 2010). Thus, the impact of a tool on the emotional state of the learner needs to be carefully considered. Indeed, assessing the impact of such tools is difficult, because the very act of measuring it may influence the learner and alter their emotional state and interaction with the learning modality or technology.

In contrast to direct effects of technology on metacognition and SRL, pairing active learning with technology (e.g., flipped classroom teaching) may hold the keys to *indirectly* helping students improve critical thinking skills, because teachers (and fellow students) have more classroom time to invest in offering feedback and helping to correct thinking when the background facts are presented to students by machines (see Chap. 6) (van Vliet et al., 2015). However, the ultimate outcome of combining technology that supports self-regulated learning, together with in-class active learning sessions and small group work, on student metacognitive development is unclear and merits more exploration (see Chap. 6). For this reason, current efforts aimed at using technology to enhance metacognition and promote development of SRL integrate multiple forms of technology with pedagogical methods (Azevedo et al., 2010). That said, there are many open questions surrounding how achievable this is in a classroom with time constraints, (potentially) more than one instructor with different priorities, and a heterogeneous class population.

1.3 Educational Research Should Develop Intentionally

1.3.1 Past: Significant Outcomes That Have Arisen from Innovations in Educational Technology

Although technology has caused many changes in the process of education, and although it has made great strides in accessibility for a subset of students, the results of all these technologies, in terms of learning, have been disappointing for the average student (Spector, 2020), despite the influence of visionaries like Steve Jobs. Educational technology does not advance in a vacuum. Since the millennium, there have been high-level demands for an educational revolution that includes research (Cech & Kennedy, 2005; DeHaan, 2005; Handelsman et al., 2004), and demands for educational reform have been mooted since the 1980s (AAAS, 2011; AAMC, 1984). Much of this has been driven by the belief that a learning society is propelled by technological knowledge and that the creation of a scientifically literate workforce has not kept pace with demand or international competition (National Academy of Sciences, 2007). Reformers have suggested educational technologies may be able to solve the two major problems that prevent many students from embracing and learning science, especially at the introductory university level:

1. **Students do not like engaging with lectures**. Students complain about the lectures, especially that they are bored by memorizing facts rather than exploring concepts on their own (Cech & Kennedy, 2005). Furthermore, there are high levels of attrition not only in science, both in early science courses, but also in public engagement with science, where potential scientists are turned off by the rote learning (Udovic et al., 2002).
2. **Students do not learn efficiently from lectures**. Students taught by lectures have poor retention of information after the course ends (Arons, 1983). Also, students taught by lectures have minimal or no understanding or conceptual knowledge of what biology really is, especially of three elements: problem-solving processes, epistemology of science, and subtle/precise definitional distinctions that appear on concept inventories (AAAS, 2011).

These two problems have been made much more pressing by the fact that the amount of bioscience information that there is to learn has exploded, while the durations of degree programs have remained constant (or in some cases have decreased due to shifting emphasis on experiential learning). Thought leaders have suggested that the solutions to these problems should come from innovations in: (A) pedagogies, (B) educational technologies, and (C) a combination of the two. The issue is that technology alone seems like an unlikely savior for education—its advances usually require a concurrent change in pedagogy and also in large-scale institutional and social organization. For example, we now have platforms that pick out plagiarism, and so they find it constantly, which creates problems for both faculty and students. The innovations that reformers are looking for are probably a combination of educational tech and pedagogy.

Massive Open Online Courses (MOOCs), which were the obvious combination of educational tech and new pedagogy, mooted the question of whether it is possible to mass produce formal university education at a scale that was previously unimaginable (Waldrop, 2013). The answer was "MOOCs do not work as hoped, but there are still new opportunities" (Jordan, 2015; Konnikova, 2014), especially for informal learning, continuing professional development, computer programming, and training teachers. Obviously, other educational technologies have changed how students access and learn some things, but are they also mostly hype? Are we really revolutionizing education, or are we just making incremental changes around the edges?

We are not the first to ask this (Elrod, 2010; Spector, 2020). Robert Kozma made an eerily prescient prediction in 1994, before streaming TV, online banking, or Amazon were let loose on the public:

> In the not-too-distant future, we will be faced with a situation where telephone, cable television, and digital computer technologies will merge [. . .] If by then [. . .] we have not forged a relationship between media and learning—this capability may be used primarily for interactive soap operas and online purchasing of merchandise with automatic funds transfer.

Kozma's point was that technology could provide an extraordinary opportunity for improving education but that this opportunity could easily be squandered on consumerism and entertainment, especially if led by technologists for profit. We propose that major educational advances will require intention. There is a visionary example of intentional use of technology and new media that delivered a clearly beneficial educational outcome: the television show Sesame Street. It was developed and researched by Children's Television Workshop, so it has been one of the most carefully researched educational interventions, both for individuals and at scale (Ball & Bogatz, 1970; Cook et al., 1975; Fisch et al., 1999; Mares & Pan, 2013). No doubt Sesame Street has made children more literate, but did it really create the learning revolution via technology as intended? Yes, Sesame Street delivered literacy and social norms to millions of children all over the world, also providing guidance to teams developing local language versions within their cultural norms. Admittedly, the learning that Sesame Street activated was not instantaneous, but it was almost effortless to the children, cost-free to the parents, accessible to all, and extraordinarily inclusive to the societies of its time.

There is no Sesame Street counterpart for university bioscience that has made young people better biologists, although efforts at adding video to biology teaching have been made by many organizations (e.g., Khan Academy and Crash Course), but these have not revolutionized the net learning of our students (Petrilli, 2018). Perhaps the clearest example of the revolution in bioscience education can be seen in the photographs of undergraduate medical students in Fig. 1.3. The upper photo shows learning—and learners—from the 1950s at a well-known medical school in London, and the lower photo shows contemporary medical students at the same university. Note first the simulation suite, informal clothes, and the fact women were previously excluded and are now a majority of the students at that medical school; these pictures tell an undeniable story of previously unimaginable change, with vastly expanded technological knowledge, access by students to that technological knowledge, and inclusivity at center stage. What is missing from the photos is the fact that the contemporary medical school trains four times as many students per yearly cohort. Education thought leaders may have taken for granted the historically unprecedented change in opportunities and participation rates in higher education (Our World in Data, 2014). The educational revolution has already happened, and is still happening, but the revolution is more a story of inclusivity and social learning rather than of "machines that teach." Technology has played a supporting role in the educational revolution all around us, but advances in culture and finance have been the stars of the show for driving genuine leaps in education.