Practical Strategies for Collaboration across Discipline-Based Education Research and the Learning Sciences

Melanie Peffer†* and Maggie Renken
Educational Psychology, Special Education, and Communication Disorders, Georgia State University, Atlanta, GA 30303

ABSTRACT

Rather than pursue questions related to learning in biology from separate camps, recent calls highlight the necessity of interdisciplinary research agendas. Interdisciplinary collaborations allow for a complicated and expanded approach to questions about learning within specific science domains, such as biology. Despite its benefits, interdisciplinary work inevitably involves challenges. Some such challenges originate from differences in theoretical and methodological approaches across lines of work. Thus, aims at developing successful interdisciplinary research programs raise important considerations regarding methodologies for studying biology learning, strategies for approaching collaborations, and training of early-career scientists. Our goal here is to describe two fields important to understanding learning in biology, discipline-based education research and the learning sciences. We discuss differences between each discipline's approach to biology education research and the benefits and challenges associated with incorporating these perspectives in a single research program. We then propose strategies for building productive interdisciplinary collaboration.

Following 20 years of work considering what and how students are learning in undergraduate science, technology, engineering, and mathematics (STEM) classes, a robust database of evidence now underscores the necessity of reevaluating how we teach in STEM classrooms (Freeman *et al*., 2014; Dolan, 2015). Calls for a "second generation" of research on undergraduate STEM education (Freeman *et al*., 2014; Dolan, 2015) reflect great advancement in the field of discipline-based education research (DBER) but also point to a pivotal moment. We are not the first to suggest that this pivot should be away from distinct camps of related research and toward the interdisciplinary integration of these camps. In fact, Coley and Tanner (2012) point out that interdisciplinary collaborations between DBER and the learning sciences present a novel approach to understanding and improving STEM education. We extend this claim—touting the collaboration of these fields as providing not only novel but also crucial insight. Our aim here is to advance discussion surrounding the second generation of life sciences education research and provide practical strategies for collaboration across the life and learning sciences.

The notion of a necessary shift toward interdisciplinary approaches to DBER is reflected in the National Research Council (NRC, 2012) report, *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*. According to the report, high-quality research programs in DBER require individuals who intimately understand what it means to be an expert in a domain and the challenges associated with developing such expertise *and* an understanding of work in the behavioral and social sciences that describes findings related to human cognition, motivation, and learning. Although the importance of interdisciplinary research is highly endorsed, few interdisciplinary studies exist (NRC, 2012). As pointed

Debra Tomanek, *Monitoring Editor*
Submitted December 11, 2015; Revised April 15, 2016; Accepted April 26, 2016
CBE Life Sci Educ December 1, 2016 15:es11
DOI:10.1187/cbe.15-12-0252
*Address correspondence to: Melanie Peffer (melanie.peffer@unco.edu).
†Present address: Biological Sciences, University of Northern Colorado, Greeley, CO 80639.

out in the report, the corpus of DBER research lacks robustness because of the lack of studies incorporating cognitive and educational psychology perspectives. Consequently, the committee that produced the 2012 report recommends that future research in DBER draw on decades of knowledge and experience produced by educational and cognitive psychologists. They argue that drawing from the existing psychology knowledge base will facilitate future DBER that expands focus to the mechanisms underlying learning. Furthermore, current DBER is divided into distinct subfields with little collaboration among science domains and with the learning sciences (Talanquer, 2014).

In this essay, we first attempt to operationalize DBER and the learning sciences as distinct disciplines in order to highlight the benefits of incorporating disciplinary knowledge from each into a single program of study. We introduce an analogy for synergy across these disciplines and describe how such synergy contributes to both theory refinement and classroom applications. We then identify challenges associated with interdisciplinary collaboration specific to DBER and the learning sciences. We close with suggested strategies for forming and maintaining productive interdisciplinary collaborations.

DISCIPLINE-BASED EDUCATION RESEARCH

DBER (pronounced "dee-burr") is an approach to understanding learning, practices, and the development of expertise in a specific domain, typically in the sciences, by scholars within that domain. For example, DBER scholars can be found within domains such as astronomy, biology, chemistry, engineering, geology, and physics (NRC, 2012). DBER requires disciplinary expertise, which allows for perspective on the specific challenges associated with teaching and learning within the discipline. Very generally, discipline-based education researchers often seek to ascertain how learning occurs within a discipline and what pedagogical strategies are most effective at promoting student learning (NRC, 2012).

THE LEARNING SCIENCES

The broad aim of learning sciences research is to understand learning, cognition, and development in both laboratory and classroom settings (Barab and Squire, 2004). Learning scientists' foci run the gamut from basic research on learning processes to large-scale evaluation of education interventions (Nathan and Wagner Alibali, 2010). Much like discipline-based education researchers, learning scientists often do work intended to inform evidence-based teaching practices. While the learning sciences field extends beyond psychology, learning sciences research draws on practices and principles originating in psychological science. Learning sciences research is not solely focused on theory development; instead, it extends to consider practical applications and refinement. In fact, some have described the field as "eduneering" because of its parallels with engineering research (Nathan and Wagner Alibali, 2010). For example, learning science research often involves attention to design features and the iterative refinement of pedagogy and instructional tools. Along these lines, Nathan and Wagner Alibali (2010) highlight four main themes in learning sciences research. Learning sciences research 1) is driven by a translational approach in order to bridge *research and instructional practice*, 2) seeks to improve the relationship between *theory and instructional practice*, 3) assesses educational interventions through *design-based research and experimental studies*, and 4) includes consideration of the *sociocultural context* in which learning occurs.

A few considerations are noteworthy with regard to our descriptions of DBER and learning sciences research. First, unlike discipline-based education researchers, learning sciences researchers do not necessarily narrow focus to particular domains or disciplinary content (e.g., biology) but rather focus on some component of learning (e.g., coordination of theory and evidence) that may be studied across domains and disciplines. Consequently, although some parallels can be seen between the learning sciences and DBER (e.g., bridging research and the practice of teaching), learning scientists typically approach research from different, albeit complementary, perspectives and practices than discipline-based education researchers, which we discuss in further detail below. It also is important to note that both DBER and the learning sciences, as we have conceptualized them here, are inherently multidisciplinary fields. That is, within each of these fields, multiple disciplines (e.g., biology and physics in DBER; cognitive science and educational psychology in learning sciences) provide different perspectives on the same issue (Stember, 1991). We distinguish this use of the term "multidisciplinary" from our use of the term "interdisciplinary" by defining interdisciplinary research later in this essay. Because a detailed discussion of this distinction is outside the scope of this paper, we also direct readers to Huutoniemi *et al*. (2010) for an in-depth review of interdisciplinarity.

EXAMPLES OF COMPLEMENTARY WORK FROM DBER AND LEARNING SCIENCES

We further differentiate DBER and the learning sciences by providing examples of recent work from each discipline that approach similar questions of interest to life sciences education research (Table 1). We have chosen to highlight articles from each discipline that investigate model-based learning and concept mapping in life sciences education. Four papers were chosen based on publication date (specifically, those published within the past year), prestige of the journal, and focus on principles related to life sciences education. Note that the following section is not meant as a critique of these articles, nor is it intended to be an exhaustive literature review. Rather, each of the highlighted papers was chosen to distinguish practices in each field on related subject areas.

The first pair of papers chosen investigates model-based learning. The DBER paper (Reinagel and Speth, 2016) examines models related to the central dogma produced by students during class exams. The learning sciences paper (Mulder *et al*., 2016) examines the utility of partially completed models for supporting student learning in a unit exploring the glucose–insulin regulatory system. The second pair of papers investigates the relationship between concept mapping and quality of writing (DBER; Dowd *et al*., 2015) and a specific type of concept map, the knowledge integration map, as an output of student understanding of principles of evolution (learning sciences; Schwendimann and Linn, 2016). The latter study also investigates the role of critique on knowledge integration.

Given that each of the studies mentioned above has related but separate research questions and that each represents only a small percentage of a larger corpus of work, we will focus on broad distinguishing features of each that best characterize

TABLE 1. Examples of complementary life sciences education research

Citation	Journal	Field of researchers	Content area	Population of interest
Reinagel and Speth, 2016	*CBE—Life Sciences Education*	DBER	Model-based learning	Undergraduates
Mulder *et al.*, 2016	*Journal of Research in Science Teaching*	Learning sciences	Model-based learning	Adolescents
Dowd *et al.*, 2015	*CBE—Life Sciences Education*	DBER	Concept maps	Undergraduates
Schwendimann and Linn, 2016	*Journal of Research in Science Teaching*	Learning Sciences	Concept maps	Adolescents

each discipline. One major area of differentiation between DBER and learning sciences literature is the population of interest. In both DBER papers mentioned above, as well as the majority of DBER papers, research is conducted with undergraduate students. The two learning sciences papers focus on high school samples, but the learning sciences literature spans ages from childhood to adulthood and also encompasses both formal and informal learning environments. Furthermore, in both DBER papers discussed here, the investigator also served a role as instructor for the course. While this is often the case in the DBER literature, it is not the norm in the learning sciences literature. As stated above, an important distinction between DBER and the learning sciences is that discipline-based education researchers are discipline experts and subsequently are often instructors in their field.

A difference in disciplinary perspective also is reflected in the central focus of each article. For example, in the papers examining model-based learning, the DBER paper (Reinagel and Speth, 2016) spends significant time in the introduction discussing pedagogical challenges associated with molecular genetics and in the methods section, very specific details are included about the course context and method of instruction as an active learner-centered pedagogy. This is in contrast to the learning sciences article (Mulder *et al*., 2016), which includes few details about instruction or pedagogical challenges in life sciences education, other than what is necessary to set the context for the study. In their introduction, Mulder *et al*. (2016) do not discuss life sciences education and instead focus solely on the theoretical framework and previous research on model building. The learning sciences paper that examines concept mapping (Schwendimann and Linn, 2016) includes some discussion of the teaching of evolution, but the majority of the introduction focuses instead on theory and prior work. We see differences in the use of theoretical framing in the DBER papers, as Reinagel and Speth (2016) provide some theoretical framing for their article, whereas Dowd *et al*. (2015) provide very little.

A MODEL OF INTERDISCIPLINARY COLLABORATION: THE SECOND GENERATION OF LIFE SCIENCES EDUCATION RESEARCH

Both DBER and learning sciences research are relevant to life sciences education. Research in the learning sciences is based on robust methodology and decades of empirically driven theory refinement. Researchers within DBER have experience that yields insight into the specific learning demands of a given domain. The combination of these perspectives to create an interdisciplinary approach will be an essential component of the second generation of life sciences education research. But like most widely used terminology, the phrase "interdisciplinary research" has been operationalized in various, inconsistent ways. For clarity, we define interdisciplinary research as the integration of the contributions and perspectives of at least two disciplines to address some problem or issue (cf., Stember, 1991; Nissani, 1997). Interdisciplinary research requires each person contribute his or her expertise to accomplish the group's collective goals (Haythornthwaite *et al*., 2006). The key distinction between interdisciplinary collaboration and other forms of collaboration (e.g., cross-disciplinary or multidisciplinary) is the former's emphasis on the meaningful, goal-oriented synthesis of ideas. Only when multiple fields are brought together in such a meaningful and synergistic manner, does innovative and novel interdisciplinary research result (Bronstein, 2003).

We illustrate interdisciplinary synergy with a three-dimensional triangular prism (Figure 1). Our prism consists of three major stakeholders in life sciences education—discipline experts, learning scientists, and educators.[1] Each stakeholder is represented as a distinct rectangular face of the prism. For the purposes of this paper, we are focusing on two stakeholders (represented by the textured faces in Figure 1, B and C), discipline-based education researchers and learning scientists. When the disciplines are connected, two triangular ends of the prism are formed (represented as the textured faces of the prism, Figure 1A). These ends represent two putative aims (and eventual outcomes) of a meaningful combination of different perspectives to address a common goal. For our purposes of addressing life sciences education research, the aims are theory development and classroom applications. Although we only discuss these two aims here, others may also be possible.

Our illustration does not necessarily represent the current state, but a metaphor that we contend is a useful analogy for how interdisciplinary collaboration *should* function. Figure 1 is intended to clarify that, although researchers in the learning sciences and DBER typically have common research aims, they approach these with their own expertise, theories, methods, and interpretations of findings. Interdisciplinary collaboration requires an understanding and, often missing, appreciation of the perspective and unique contribution collaborators offer each other. The goal is for the two fields to be stitched together in a meaningful way that strengthens our collective understanding.

[1]Although DBER researchers are often educators within the discipline as well, for our purposes here, we are referring to K–12 educators. Although the perspective of educators is an important part of the interdisciplinary prism, we have chosen to focus this essay around the perspectives of the discipline-based education researcher and learning scientists. We do not mean to downplay the role of this component in understanding learning principles and classroom applications, but we limit our discussion of the topic, since it outside the scope of our current aims. We hope researchers will pick up on this component for further development in future work.

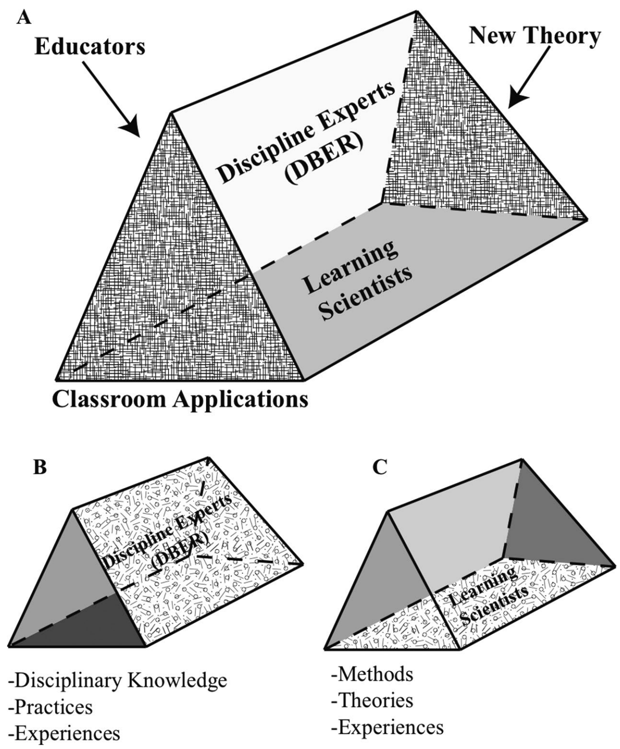

FIGURE 1. A three-dimensional interdisciplinary prism illustrates the roles of educators, discipline-based education researchers, and learning scientists in interdisciplinary biology education research (A). We highlight two faces of the prism (B and C) to distinguish the two stakeholders we focus on in this paper—discipline-based education researchers and learning scientists—and the unique perspectives from each group. As we argue in this paper, varied expertise and theoretical and methodological approaches do not have to converge but, if stitched together in a meaningful way, can yield novel theory and new classroom applications.

DIFFERENTIATING DBER AND LEARNING SCIENCES PERSPECTIVES

According to our model, successful interdisciplinary work requires a combination of unique perspectives. These unique perspectives, although an integral part of the utility and value of an interdisciplinary approach, may also present challenges. Now that we have outlined some broad differences between the two fields, we move to a discussion of differences between the two fields that can also be barriers to successful collaboration. Successful interdisciplinary collaboration, as shown in the social psychology literature, relies on collaborators recognizing and attending to discipline-specific differences (Bronstein, 2003; Gooch, 2005).

We begin with a discussion of DBER and the learning sciences stemming from different scholarly traditions. We start here, because differences in traditions of scholarship highlight a substantial barrier to collaboration due to a history of strife between the "hard" and "soft" sciences. We draw from research on nature of science (NOS) to describe how the practice of science most likely differs for discipline-based education researchers and learning scientists. We hope that our highlighting of differences in the so-called soft and hard sciences in relation to NOS understanding will better prepare researchers to engage in interdisciplinary dialogue with colleagues with diverse scientific training. We also discuss differences in research practices, including the use of theory and distinct research paradigms. Although methodologies in the two fields are beginning to converge, distinctions remain.

Scholarly Traditions

> The dismissive attitudes scientists have toward psychologists isn't rooted in snobbery; it's rooted in intellectual frustration. It's rooted in the failure of psychologists to acknowledge that they don't have the same claim on secular truth that the hard sciences do. It's rooted in the tired exasperation that scientists feel when non-scientists try to pretend they are scientists.
>
> Alex B. Berezow (2012)

> In science, when human behavior enters the equation, things go nonlinear. That's why Physics is easy and Sociology is hard.
>
> Neil deGrasse Tyson (2016)

The first quote above appeared in the *Los Angeles Times* in 2012 in response to an op-ed piece titled "Stop Bullying the 'Soft' Sciences," in which a psychologist describes frustration at the lack of respect shown to the social sciences by those in the hard sciences (Wilson, 2012). The claim that the social sciences are somehow inferior to other science disciplines is not new; a 1912 paper describing the history and status of psychology in the United States claims that psychology is "not very high on the honor roll among other academic subjects" (Ruckmich, 1912, p. 530). What is the root of such intellectual snobbery and why has it persisted? Such lack of understanding and appreciation for science practices across disciplines is a major barrier to interdisciplinary collaboration, especially of the type we propose in this essay, which involves researchers from "soft" sciences traditions (which arguably encompass several branches of psychology and stems from psychology traditions; here, the learning sciences) and the "hard" sciences (DBER).

Paul Feyerabend's provocative work challenges the sanctity with which some scientists perceive the practice of science. Feyerabend, a science philosopher, compares science with religion, going so far as to state that "science is a religion" (1975, p. 54). He suggests that viewing science too ideologically and becoming dogmatic impairs the overall progress of science. By strictly adhering to certain principles of what science is (which is influenced by social and cultural perspectives), we limit our ability to solve problems in a creative and innovative manner. Science knowledge is thought to be theory laden, meaning that how a scientist interprets and produces knowledge is a function of his or her prior knowledge, personal epistemology, training, experience, and discipline (Lederman *et al*., 2002). A single unifying scientific method does not exist, and methodologies within disciplines are a factor of the types of research questions proposed and the phenomena of interest.

What makes a science "hard" is up to interpretation. There are no firm rules delineating the two, but a fundamental issue for differentiating hard and soft sciences lies in replicability and predictability (Howard, 1993). Can data produced in one part of the world be repeated in a different location? Do these data allow for accurate predictions to be made? A major challenge of any research interested in studying living entities, whether students in a classroom or mice in a lab, is that the subjects are not identical. Although efforts are made in biological research to use inbred mouse strains to reduce variability, this is not possible with human participants. Too many factors influence how students learn, which leads to issues with replicability and predictability. As Howard (1993) points out, if the definition of a hard science is based on a near-perfect ability to predict phenomena, then the social sciences can never be considered "hard" science because of the variability of human behavior. To suggest that one is more or less scientific than the other is to risk sacrificing scientific rigor for ideology. As Feyerabend warns, focusing on ideology rather than rigor leads to the suppression of innovation. One discipline is not "more scientific" than the other—each discipline concerns itself with different phenomena, which consequently necessitates different approaches and traditions. These discipline-specific approaches and traditions are reflected in their different practices, which we describe next.

Differences in Practices

Use of Theoretical Frameworks. Theoretical frameworks can be difficult to conceptualize across disciplinary lines, because "theory" has different meanings in biology research and in learning sciences research. Consequently, when pursuing interdisciplinary research, how and why to ground research in a theoretical framework can be challenging for those outside the learning sciences. We will now describe how the usage of the word "theory" differs between disciplines.

A theory is an explanation for a series of seemingly unrelated phenomena that is well-supported and used to guide scientific investigation. Because scientific theory may often be based on unobservable phenomena, we rely on indirect evidence to support or refute a given theory (Lederman *et al*., 2002). The most commonly used and taught theories in biology, such as evolutionary theory or cell theory, are supported by a large body of data and are typically accepted throughout the scientific community. This is different from research in the learning sciences. For example, in educational psychology, one discipline under the umbrella of the learning sciences, multiple theories exist for explaining learning. Theories in educational psychology explain mechanisms of learning from one of a variety of camps and subcamps, such as behaviorist, information processing, or developmental, and are ever evolving from classic foundations such as those laid by Jean Piaget's work on cognitive development or Lev Vygotsky's theories of social cognition. Unlike evolutionary theory, which crosses multiple subdomains within biology, there is no single theory of learning that generalizes across all subdomains within the learning sciences. Historically, psychologists have been trained in a given theoretical camp. Consequently, in learning sciences research papers, authors typically designate a specific theoretical framework as the basis for a given study and then situate study findings within the contexts of existing theory.

Research Methodologies. In addition to differences in the use of theory, differences in research methodologies may also pose potential barriers for interdisciplinary collaboration. We focus on three methodological approaches useful for education-relevant research: design-based research, psychology lab-to-classroom studies, and microgenetic research. We have chosen to highlight these approaches, because, in our experience with interdisciplinary collaborations, we have found these to be useful paradigms but most likely to be misunderstood across discipline lines. Such misunderstanding may stem from issues with terminology or with larger issues related to the conceptual underpinnings of approaching research a certain way. This is not an exclusive list, but the methodologies discussed here serve as valuable illustrations of possible methodological barriers to collaboration.

Design-Based Research. Although lab-based psychology experiments (discussed below) are useful for identifying mechanisms of learning in a controlled setting, learning is often assessed solely in the context of real-world classrooms. Executing research within classrooms is inherently difficult due to the inevitable noise and variability found within classrooms. Design-based research integrates a series of approaches intended to understand learning in the context and noise of classrooms (Barab and Squire, 2004).

Design-based research methodology is based on research in engineering fields and focuses on iterative changes based on shifts in understanding. This focus on iterative design helps account for the noisiness inherent in classrooms, because it provides the researchers with a method for adjusting ongoing research in response to unanticipated events or considerations that may occur as the study progresses (Nathan and Wagner Alibali, 2010). In the literature, design-based research can be found as a description of an initial study that will later be iteratively refined (such as Mega Subramaniam *et al*., 2015) or of a series of studies described in one artcle, each with a refinement over the last (such as Hickey *et al*., 2012).

In some ways, design-based research is more similar to biology research than psychological lab research. For example, in the course of addressing how a drug treatment will impact a population of stem cells, a biologist iteratively adjusts research questions and approach based on current findings. Even with a hypothesis-driven approach, it is not always possible to foresee all possible outcomes and necessary refinements. Furthermore, iterative refinement can span multiple publications from a variety of labs that all contribute to a larger understanding of a certain research question. Although these multiyear studies are common in biology and medical research, they are still uncommon in education research and provide an opportunity for expansion of design-based research.

In the context of education, rather than solely demonstrating that an intervention works, design-based research emphasizes the testing and generation of theory within an authentic natural context for learning, such as the classroom (Barab and Squire, 2004). For example, design-based research connects education interventions with existing theory and may also generate new theories about how people think and learn (Barab and Squire, 2004). The larger goal of design-based research is to create a research approach that is more likely to result in translation of education research into practice (Anderson and Shattuck, 2012). Results of design-based research inform our understanding of the optimal context for learning, often by describing the environment that produced certain learning outcomes (Anderson and Shattuck, 2012).

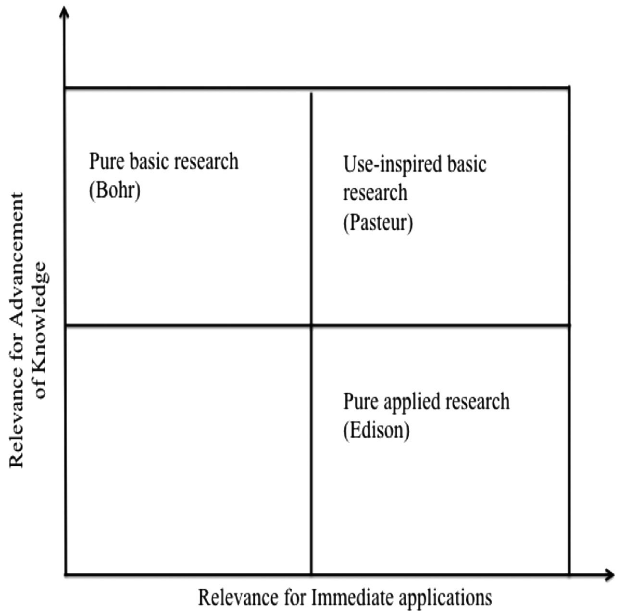

FIGURE 2. Quadrants of research based on aims related to advancing knowledge or applied use. DBER and learning sciences research is often housed in Pasteur's quadrant. Illustration adapted from Stokes (1997) and National Academy of Sciences, National Academy of Engineering, and Institute of Medicine (2010).

Psychology Lab-to-Classroom. Much like the bench-to-bedside model in medical research, learning sciences research sometimes follows a translational, psychology lab-to-classroom approach. Klahr and Li (2005) describe this model for research as motivated by two aims, originally described by Stokes (1997). According to Stokes, research motivation can be described in terms of two dimensions. In the first dimension, research is aimed at advancing basic understanding. In the second dimension, research is aimed at developing practical applications to the real world. Stokes then goes on to characterize research strategies represented in each quadrant by giving examples of prominent scientists. Research that aims to advance basic understanding with no emphasis on applications falls squarely in Bohr's quadrant (see Figure 2). Klahr and Li (2005) describe Klahr and colleagues' line of cognitive science research on understanding the development of scientific reasoning skills—particularly control of variables strategy (CVS)—as falling in this quadrant. This early line of work occurred in traditional experimental psychology lab settings and used straightforward experimental design with the solitary aim of understanding how a set of cognitive mechanisms and processes develop.

Research that centers on use in applied settings without consideration of advancement of basic understanding falls in Edison's quadrant. Research in Edison's quadrant aligns with engineering, emphasizing *what* works rather than *how* it works. This approach is appealing in science education research, because it removes the hypothetical nature of much psychology lab research and yields instructional approaches that can be applied and assessed practically, despite the many confounds and challenges posed in the classroom.

Klahr and Li (2005) go on to argue that work that falls in a third quadrant, Pasteur's—with focus on *both* use and understanding—is most beneficial in its reconciliation of the challenges associated with pure basic research (e.g., utility in the real world) and pure applied research (e.g., replicability, ability to translate to real-world settings). For example, following psychology lab–based work examining the development of CVS, Klahr and colleagues extended work to examine the impact of instruction on CVS. A lab-to-classroom approach requires meaningful and intentional shifts from carefully controlled experimental work aimed at understanding foundational learning principles to classroom-based studies of how prescribed learning mechanisms function, change, and respond to instruction, curriculum, and technology. Oftentimes, the latter classroom-based research raises additional questions that are not easily answered in the relative experimental chaos of the classroom. An important aspect of psychology lab-to-classroom research is the effortful shift back to careful, lab-based experimentation once such questions arise in the classroom. This feedback loop allows researchers to contribute to both understanding *and* use through careful methodological design that relies on psychology and science education research perspectives. Almost a decade ago, in a brief report on the impact of such an approach, Linn and Bjork (2006), point to the intricacies and complexities raised by comparing consistencies and inconsistencies in psychology lab– and classroom-based research. Much like what has been said earlier regarding design-based research, Linn and Bjork (2006) purport that findings stemming from lab-to-classroom research may provide valuable design principles for optimizing science instruction.

Microgenetic Research. The etymology of "microgenetic" refers not to the study of genetics but reflects an archaic use of the term "genetic." The "genetic method" refers to a methodology in which an extended investigation is used to study developmental sequences (Kai, 1939). The first microgenetic experiments are traced to Heinz Warner, who performed so-called "genetic experiments" to describe the sequence of states that occurred during a psychological event (Siegler, 2006). Developmental psychologists first used microgenetic methods as a means for determining how cognitive processes change while an individual is developing. Rather than assessing the cognitive growth that an individual may have after a year of school, microgenetic studies assess real-time change and growth on a continuous basis. Microgenetic methods have three key features: 1) observations span a time in which an individual is rapidly growing in ability; 2) many separate observations are made, and the total number of observations made is dependent on the expected rate of change of the phenomena of interest; and 3) observations inform theories about the processes that underlie observed changes (Siegler, 2006; Siegler and Crowley, 1991).

Microgenetic studies are not the same as cross-sectional or longitudinal studies that seek to determine when, or whether, certain abilities develop over time; instead, the emphasis of a microgenetic approach is to provide detailed information about *why* and *how* a certain ability develops (Siegler, 2006). Microgenetic methodology is versatile and appropriate to use throughout the lifespan to study a wide variety of processes, including learning; can be used in laboratory or classroom settings; and has a track record for utility in testing the predictions of major theories of cognitive development (Siegler, 2006). In the context of educational research, microgenetic studies provide detailed insight into how a student is learning over the course of an intervention. For example, Disessa (2014) used a microgenetic method for studying adolescents' physics learning. Laski and Siegler (2014) used a microgenetic method to examine how kindergartners learn basic math skills through game play.

BARRIERS TO INTERDISCIPLINARY COLLABORATION

Although the learning sciences and DBER clearly have overlapping interests, and the distinctions between the two are important for interdisciplinary collaboration, these differences also lead to barriers. We first highlighted differences in traditions of scholarship and the lack of understanding and respect that exists between the hard and soft sciences. This lack of understanding and respect between the fields is a serious barrier toward interdisciplinary collaboration. This intellectual snobbery leads to a strong adherence to one's perspective at the expense of understanding the methods and practices of another discipline. As we have stated throughout the essay, and as echoed in social psychology literature, successful and innovative interdisciplinary collaboration requires a synergistic, meaningful combination of two different perspectives. Consequently, if underlying tensions exist because of "my science" versus "your science" or arrogance about being from a "superior" discipline, it is extremely difficult if not impossible to attain synergy.

In our discussion of what distinguishes DBER and the learning sciences, we focused extensively on the differences of practices, particularly the use of theory and methods. For example, different understandings of how theory is used in research between discipline-based education researchers (who trained in disciplines outside the social sciences) and learning scientists may contribute to the lack of theoretical framing in a great deal of the DBER literature. This leads to problems communicating to a wider community, because failure to properly situate findings within existing theoretical frameworks and literature makes it difficult for those outside DBER to understand and appreciate the relevance and importance of DBER work. Application of theory to teaching and research is not a topic to take lightly. Disregard for theory building with respect to existing theory only works to move the field further from functioning as a cumulative science. In fact, the existence and impact of a field flooded with multiple theoretical explanations for the same phenomenon has led to its description as the "toothbrush problem" (i.e., everyone has one and no one wants to use someone else's; Mischel, 2008). Mischel (2008) recommended that, instead of engaging in parallel play around related problems, researchers make it the norm to connect closely related work, regardless of disciplinary boundaries.

We and others (e.g., Coley and Tanner, 2012) note that research topics in life sciences education research are missing the connection of their findings to new or existing theoretical frameworks. Although theories are approximations of learning and subject to revision in response to new research, they serve a valuable function in situating educational design. Teaching based on intuitions, how a topic is typically taught within a domain, or bandwagon teaching based on the newest educational technology risks sacrificing quality, research-driven teaching (Nathan and Wagner Alibali, 2010). Situating teaching and research within a theoretical framework provides the best chance at success, because empirically tested theories should serve as reliable starting points for developing learning experiences and research questions.

In addition to challenges associated with different understandings of theory, methodological differences may interfere with the interpretation of results and application of conclusions across the two fields. But perhaps more problematically, we also see such differences as a hindrance to successful interdisciplinary collaborations. In the preceding section, we discussed three methodologies that are generally characteristic of learning sciences research—design-based research, lab-to-classroom studies, and microgenetic methodologies. Although it may be possible that some DBER studies use a methodology similar to design-based research, they are not framed as such and may also not be perfectly aligned with how learning scientists operationalize design-based research practices. In the examples of design-based research that we cite in this article, both specifically state the use of a design-based research approach and situate the article as either the first iteration (Mega Subramaniam *et al*., 2015) or as a series of small studies that build on each other (Hickey *et al*., 2012). If DBER practitioners are using a design-based research approach that is typical of the learning sciences, the lack of following learning sciences practices in their reporting of research leads to a disconnect between the two disciplines, even though the research questions are of interest to a broad audience. This, much like discipline-specific use of "theory," underscores how not attending to differences in disciplinary practices impairs the progress of research by impairing communication across disciplinary lines and resulting in less interdisciplinary and more siloed research programs.

Furthermore, microgenetic and psychology lab–based studies are not common in the DBER literature but may be useful methodologies for DBER researchers. In our own experience, while resources for exploring the motivations underlying methodological approaches are available, synthesizing these approaches (e.g., understanding their similarities and differences, identifying what aspects apply to one's own work and how to apply them) is often daunting and cumbersome. The difficulty of this task lies not only in the size of the task but in first being motivated to look outside one's own paradigm, then knowing where to look, and finally deciphering similar constructs shrouded in different terminology across approaches.

PRACTICAL STRATEGIES FOR COLLABORATION

Having pointed to areas of convergence (e.g., with regard to aims) and divergence (e.g., with regard to the use of theory) across DBER and learning sciences, we now shift to delineating clear strategies for forming, fostering, and benefiting from interdisciplinary collaborations. We reiterate our point in the design of Figure 1, that there is strength in varied methodological and theoretical frames for understanding learning principles and classroom applications. Our intent is not to suggest that DBER and learning sciences researchers aim toward overlapping work but instead identify meaningful synergies to advance science learning and education.

Thoughtfully Consider Your and Your Colleagues' NOS Understanding

There is no single way to approach science, and practices vary widely both across and within disciplines. We suggest exploring literature on NOS and NOS inquiry (such as Lederman *et al*., 2002; Lederman, 2007; Lederman and Lederman, 2014; Deng *et al*., 2011) as well as classics such as Thomas Kuhn's *The Structure of Scientific Revolutions* (2012) and Alan Chalmers' *What Is This Thing Called Science?* (2013) and the modern *Ignorance: How It Drives Science* by Stuart Firestein (2012). We suggest that thoughtful consideration of what the practice of science means to us individually is an important first step to engaging in dialogue with others who may practice science differently.

Engage in Effortful Discussion across Disciplinary Lines to Identify and Clarify Differences

An appreciation for each discipline is the power and benefit of interdisciplinary work, and we encourage those interested in interdisciplinary collaboration to discuss with colleagues from different disciplines how the practice of science varies. Building successful interdisciplinary collaborations starts by forming relationships with experts from a different field and seeking to understand one another's disciplines (Gooch, 2005; Powell *et al*., 1999). Although we point to differences in methods and theory that we have observed working across disciplinary lines, each collaboration is different. Consequently, the challenges we observed may or may not align with all interdisciplinary collaborations. Therefore, for interdisciplinary collaborations to succeed, researchers must engage in a concerted effort to understand the disciplinary practices of their collaborators without sacrificing their own perspectives.

As a first step, you may wish to find someone in a discipline different from yours and discuss different practices. We recommend reviewing the list of universities that belong to the Network of Academic Programs in the Learning Sciences (NAPLeS). The NAPLeS website (http://isls-naples.psy.lmu.de) includes a comprehensive list of learning sciences faculty and participating universities along with contact information.[2] The NAPLeS network was formed as part of the educational mission of the International Society of the Learning Sciences (ISLS). Another way to meet collaborators is to attend either of the conferences organized by ISLS. The International Conference for the Learning Sciences and the Computer-Supported Collaborative Learning Conference occur biennially. ISLS also publishes two journals of interest, *Journal of the Learning Sciences* and *International Journal of Computer-Supported Collaborative Learning.* Other organizations with useful resources and conferences include EARLI, the European Association for Research on Learning and Instruction, which includes such special interest groups as higher education, quantitative and qualitative approaches to learning, instruction and learning, and teaching in culturally diverse settings. As of the writing of this article, EARLI includes researchers from 61 different countries and meets biennially. The Cognitive Development Society (CDS) meets annually and is a group of individuals who are interested in cognitive process and cognitive development, including cognitive processes that underlie human comprehension of biology. CDS publishes the *Journal of Cognition and Development*, which includes not only research articles but also articles describing methodological techniques. Division 15 of the American Psychological Association (APA), educational psychology, is a venue for anyone with an interest in research, teaching, and/or practice within educational settings. Division 15 of the APA also publishes *Educational Psychologist*. For those who are coming from a learning sciences perspective and are interested in collaborating with a DBER researcher, the Society for the Advancement of Biology Education Researcher meets annually and lists universities with biology education research graduate programs on its website.

Become Familiar with Various Methodologies

Although we are not suggesting that everyone become experts in all methodologies (which defeats the purpose of interdisciplinary collaboration), we do suggest that those interested in interdisciplinary collaboration learn the basics of other methodologies. We hope that our brief review of methodologies in this essay may serve as a useful resource and starting point for those interested in growing and diversifying their methodological tool kits in order to bridge cross-disciplinary gaps. This diversified methodological tool kit allows researchers to strengthen their own research—for instance, in times when phenomena remain unexplained. Furthermore, a diversified methodological tool kit also allows researchers to broaden and complement their own perspectives through accurate interpretation of others' results. We expect that, through expanded, diversified methodological tool kits, collaborative teams of researchers will be better equipped to ask, and subsequently answer, different kinds of questions. We do not intend to suggest that methodology should blindly and wholly converge across disciplines. To do so would dilute the power of bringing together multiple research paradigms, perspectives, and strengths.

Identifying methodologies of interest may also help with the identification of possible collaborators who specialize in certain methods. As discussed above, there may be overlap in the methodologies within disciplines, but the lack of common language to discuss these methods may serve as a barrier. By understanding and appreciating the language surrounding methodologies used by each discipline, researchers can be better prepared for engaging in discussions across disciplinary lines.

When Planning Interdisciplinary Work, Create Well-Defined Roles in Which Each Person Utilizes His or Her Skill Set and Perspectives to Achieve Group Goals

"Interdisciplinary" is often used solely as a buzzword without consideration for what it means and whether or not the research proposed is in fact interdisciplinary. If you are considering an interdisciplinary approach, thoughtfully consider and discuss with your colleagues what you hope to accomplish and why. How does each individual's perspective, expertise, and skills contribute to the overall goal? Although this may not be clear at the onset of a relationship, a clear understanding of the distinction between each party and how each party will contribute to project goals are important considerations (Bronstein, 2003).

[2]We also recommend reviewing the NAPLeS website not only to identify possible collaborators but for the wealth of information available through their webinars, including those on learning and methodologies within the learning sciences.

Incorporate Interdisciplinary Training in Doctoral Programs

As part of ongoing educational reform, there have been calls to create graduate and postdoctoral programs that train individuals in teaching and learning (Handelsman *et al*., 2004; NRC, 2012). How should these programs be structured so as to best train the next generation of scientists for collaborative and interdisciplinary nature of the "second generation" of DBER? What is the best way to balance creating a cohort of young scientists who can function as discipline experts *and* are able to engage in educational research methodology? How do we train students in both DBER and the learning sciences for successful interdisciplinary collaboration? As we have mentioned previously in this essay, the value of interdisciplinary collaborations lies in the meaningful combination of different expertise. Some have suggested that graduate programs for training science education researchers should include a "broad span of disciplinary and methodological approaches [to enable students to] become comfortable working in collaborations with experts in other disciplines" (Eisenhart and DeHaan, 2005, p. 8). Although we agree that it is valuable for students to be exposed to a variety of traditions and disciplines, this must be balanced with attaining disciplinary expertise.

Rather than expose graduate students to as many different disciplines and methodologies as possible, we suggest that graduate programs train students to become experts in specific disciplines while concurrently promoting the development of the skills necessary to engage in interdisciplinary collaboration. For example, previous work has indicated that individuals with experience in successful interdisciplinary work tend to have future success in similar collaborations (Bronstein, 2003). Therefore, students could be required to interview with or interact with someone from a completely different discipline and then metacognitively reflect on that experience, potentially with additional NOS instruction, such as that proposed in the first strategy discussed here. This interaction could be framed around the student's career goals; in the case of biology education research, a student in biology could interact with learning scientists within his or her university. This strategy allows students to experience dialogue across disciplinary lines and to reflect on different practices without sacrificing their attainment of a specific expertise. This experience can be done alongside course work in NOS. Discussions of what it means to do science causes students to metacognitively reflect on and consider their own practices and compare those practices with their experience exploring the practices of others in different disciplines. As we have stated previously in this essay, thoughtful consideration and dialogue about different practices is an essential component of interdisciplinary collaboration.

Another possible solution is to allow students to pursue a certificate in a specialized area related to their research interests. For example, if a student is specifically interested in biology pedagogy, he or she could take specialized course work within the college of education or in his or her respective department about teaching to students of various ages or backgrounds. Maybe the student could do a field experience in a K–12 or informal setting such as a museum as part of this certificate. Another option would be for a quantitative methods certificate, which would allow biology education graduate students to take the same advanced statistical methods courses that educational psychology graduate students take, such as item response theory or hierarchical linear modeling. Certificate programs allow students to become discipline experts in their fields of interest while gaining complementary interdisciplinary experience and experience working with others from disparate disciplines.

CONCLUSIONS

Our goal in this essay was to provide some background for understanding the benefits and challenges related to interdisciplinary collaborations and some practical strategies for forming them. We discussed the utility and value in synergistic approaches to understanding learning in biology (Figure 1); as the second-generation of DBER unfolds, we are excited for the potential for advancing our collective understanding of how students learn science. Although DBER and the learning sciences have some fundamental differences in traditions of scholarship and research practices, both fields have similar goals and interests. The meaningful connection of these different perspectives leads to both the power and challenge for forming productive interdisciplinary collaborations. It is the meaningful combination of these perspectives that leads to novel research. We also wish to note that, although interdisciplinary research has significant benefits, each field uniquely contributes to life sciences education research. We are not suggesting that all life sciences education research hinges on interdisciplinary approaches or that the two fields completely converge, but we hope the reader will recognize the possible benefits of interdisciplinary research and the opportunities and challenges of disciplinary distinctions.

We outlined possible barriers to collaboration and also some suggested strategies for overcoming these challenges. We suggest that anyone interested in engaging in interdisciplinary research in biology education research should not only understand and appreciate the differences between fields but should pay attention to the balance between having a distinct knowledge base and allowing for interdisciplinary discussion. This essay was framed around our experience engaging in interdisciplinary research in biology education, with support from the social sciences literature. Because each collaboration is different, it may be the case that our challenges and suggested strategies are not generalizable to all cases. We hope that this essay, even if not perfectly applicable in all cases, will serve as a springboard for discussion as DBER moves into its second generation.

REFERENCES

Anderson T, Shattuck J (2012). Design-based research: a decade of progress in education research? Educ Res 41, 16–25.

Barab S, Squire K (2004). Design-based research: putting a stake in the ground. J Learn Sci 13, 1–14.

Berezow A (2012). Why psychology isn't science. Los Angeles Times. http://articles.latimes.com/2012/jul/13/news/la-ol-blowback-pscyhology-science-20120713 (accessed 15 February 2016).

Bronstein LR (2003). A model for interdisciplinary collaboration. Social Work 48, 297–306.

Chalmers A (2013). What Is This Thing Called Science? 4th ed., Indianapolis, IN: Hackett.

Coley JD, Tanner KD (2012). Common origins of diverse misconceptions: cognitive principles and the development of biology thinking. CBE Life Sci Educ 11, 209–215.

deGrasse Tyson N (2016, February 5). In science, when human behavior enters the equation, things go nonlinear. That's why Physics is easy and Sociology is hard. [Tweet]. https://twitter.com/neiltyson/status/695759776752496640 (accessed 15 February 2016).

Deng F, Chen DT, Tsai CC, Chai CS (2011). Students' views of the nature of science: a critical review of research. Sci Educ 95, 961–999.

Disessa AA (2014). The construction of causal schemes: learning mechanisms at the knowledge level. Cogn Sci 38, 795–850.

Dolan EL (2015). Biology Education Research 2.0. CBE Life Sci Educ 14, ed1.

Dowd JE, Duncan T, Reynolds JA (2015). Concept maps for improved science reasoning and writing: complexity isn't everything. CBE Life Sci Educ 14, ar39.

Eisenhart M, DeHaan RL (2005). Doctoral preparation of scientifically based education researchers. Educ Res 34(4), 3–13.

Feyerabend P (1975). How to defend society against science. In: Introductory Readings in the Philosophy of Science, 3rd ed., ed. E Klemke, R Hollinger, D Rudge, and AD Kline, Amherst, NY: Prometheus, 1998, 54–65.

Firestein S (2012). Ignorance: How It Drives Science, Oxford, UK: Oxford University Press.

Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP (2014). Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci USA 111, 8410–8415.

Gooch JC (2005). The dynamics and challenges of interdisciplinary collaboration: a case study of "cortical depth of bench" in group proposal writing. IEEE Trans Prof Commun 48, 177–190.

Handelsman J, Ebert-May D, Beichner R, Bruns P, Chang A, DeHann R, Gentile J, Lauffer S, Stewart J, Tilghman S, *et al.* (2004). Scientific teaching. Science 304, 521–522.

Haythornthwaite C, Lunsford KJ, Bowker GC, Bruce BC (2006). Challenges for research and practice in distributed, interdisciplinary collaboration. In: New Infrastructures for Science Knowledge Production, ed. C Hine, Hershey, PA: IGI Global, 143–166.

Hickey DT, Taasoobshirazi G, Cross D (2012). Assessment as learning: enhancing discourse, understanding, and achievement in innovative science curricula. J Res Sci Teach 49, 1240–1270.

Howard GS (1993). When psychology looks like a "soft" science, it's for good reason. J Theor Philos Psychol 13, 42.

Huutoniemi K, Klein JT, Bruun H, Hukkinen J (2010). Analyzing interdisciplinarity: typology and indicators. Res Policy 39, 79–88.

Kai J (1939). Genetic method. Rev Educ Res 9, 491–497.

Klahr D, Li J (2005). Cognitive research and elementary science instruction: from the laboratory, to the classroom, and back. J Sci Educ Technol 14, 217–238.

Kuhn T (2012). The Structure of Scientific Revolutions, 4th ed., Chicago, IL: University of Chicago Press.

Laski EV, Siegler RS (2014). Learning from number board games: you learn what you encode. Dev Psychol 50, 853.

Lederman NG (2007). Nature of science: past, present, and future. In: Handbook of Research on Science Education, ed. SK Abell and NG Lederman, Mahwah, NJ: Erlbaum, 831–879.

Lederman NG, Abd-El-Khalick F, Bell RL, Schwartz RS (2002). Views of nature of science questionnaire: toward valid and meaningful assessment of learners' conceptions of nature of science. J Res Sci Teach 39, 497–521.

Lederman NG, Lederman JS (2014). Research on teaching and learning of nature of science. In: Handbook of Research on Science Education, vol. 2, ed. NG Lederman and SK Abell, New York: Routledge, 600–620.

Linn M, Bjork RA (2006). The science of learning and the learning of science: introducing desirable difficulties. APS Observer 19(3).

Mega Subramaniam BSJ, Taylor NG, Kodama C, Follman R, Casciotti D (2015). Bit by bit: using design-based research to improve the health literacy of adolescents. JMIR Res Protoc 4(2), e62.

Mischel W (2008). The toothbrush problem. APS Observer 21(11).

Mulder YG, Bollen L, de Jong T, Lazonder AW (2016). Scaffolding learning by modeling: the effects of partially worked-out models. J Res Sci Teach 53, 502–523.

Nathan MJ, Wagner Alibali M (2010). Learning sciences. Wiley Interdiscip Rev Cogn Sci 1, 329–345.

National Academy of Sciences, National Academy of Engineering, and Institute of Medicine (2010). Rising above the Gathering Storm, Revisited: Rapidly Approaching Category 5, Washington, DC: National Academies Press. www.nap.edu/catalog/12999 (accessed 1 December 2015).

National Research Council (2012). Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering, Washington, DC: National Academies Press.

Nissani M (1997). Ten cheers for interdisciplinarity: the case for interdisciplinary knowledge and research. Soc Sci J 34, 201–216.

Powell J, Dosser D, Handron D, McCammon S, Temkin ME, Kaufman M (1999). Challenges of interdisciplinary collaboration: a faculty consortium's initial attempts to model collaborative practice. J Community Pract 6, 27–48.

Reinagel A, Speth EB (2016). Beyond the central dogma: model-based learning of how genes determine phenotypes. CBE Life Sci Educ 15, ar4.

Ruckmich CA (1912). The history and status of psychology in the United States. Am J Psychol 23, 517–531.

Schwendimann BA, Linn MC (2016). Comparing two forms of concept map critique activities to facilitate knowledge integration processes in evolution education. J Res Sci Teach 53, 70–94.

Siegler RS (2006). Microgenetic analyses of learning. Handbook of Child Psychology II:3:11.

Siegler RS, Crowley K (1991). The microgenetic method: a direct means for studying cognitive development. Am Psychol 46, 606.

Stember M (1991). Advancing the social sciences through the interdisciplinary enterprise. Soc Sci J 28, 1–14.

Stokes DE (1997). Pasteur's Quadrant: Basic Science and Technological Innovation, Washington, DC: Brookings Institution Press.

Talanquer V (2014). DBER and STEM education reform: are we up to the challenge? J Res Sci Teach 51, 809–819.

Wilson T (2012). Stop bullying the "soft" sciences. Los Angeles Times. http://articles.latimes.com/2012/jul/12/opinion/la-oe-wilson-social-sciences-20120712 (accessed 15 February 2016).