Comment

DBER and STEM Education Reform: Are We Up to the Challenge?

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Abstract: The extent and quality of Discipline-Based Education Research (DBER) at the post-secondary level have grown substantially in recent years. Associated research findings are central to current reform efforts to transform science, technology, engineering, and math (STEM) education in colleges and universities across the United States. The increased visibility of DBER efforts creates opportunities and challenges that should be carefully analyzed. In this contribution, I reflect on critical issues that need to be considered and addressed in advancing the fields of DBER, using the articles included in this Special Issue of the Journal of Research in Science Teaching to ground the discussion. © 2014 Wiley Periodicals, Inc. DOI 10.1002/tea.21162

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The extent, quality, and visibility of research on learning and teaching in science, technology, engineering, and math (STEM) education at the post-secondary level has increased considerably in the past 15 years (NRC, 2012a). During this period, we have not only seen an increase in the number of research studies involving students and instructors in colleges and universities, but also a major diversification in the issues under investigation. Pioneer studies mainly focused on the characterization of undergraduate students’ conceptual understanding and problem-solving abilities have paved the way for investigations that now include, among many other topics, the exploration of students’ representational competence (Kohl & Finkelstein, 2005; Kozma & Russell, 1997) and epistemological beliefs (Hammer, 1994; Mazzarone & Grove, 2013); the analysis of educational interventions designed to foster conceptual understanding (McDermott & Redish, 1999; Ruiz-Primo, Briggs, Iverson, Talbot, & Shepard, 2011), support model-based reasoning (Dauer, Momsen, Speth, Makohon-Moore, & Long, 2013; Magnani, Nersessian, & Thagard, 1999), and develop argumentation skills (Sadler & Zeidler, 2005; Walker & Sampson, 2013); and the study of faculty’s teaching beliefs and practices (Gess-Newsome, Southwell, Johnston, & Woodbury, 2003; Trigwell & Prosser, 1996). The growth in what has come to be known as Discipline-Based Education Research (DBER) has been accompanied by the development of new avenues for the communication of research findings, such as the journals CBE-Life Sciences Education, Chemistry Education Research and Practice, and Physical Review Special Topics—Physics Education Research, and by the repositioning toward DBER by long-standing educational journals such as the Journal of Chemical Education and the Journal of Engineering Education. The mere existence of this and the past special issues (Coppola &
Krajcik, 2013) on post-secondary science education in one of the most prestigious journals in science education research is a clear indication of the level of maturity reached by DBER efforts.

Calls for improving undergraduate STEM education have also increased in the past few years (AAU, 2013; Ferriny-Mundy & Güçler, 2009). Recent reports on the status and future of STEM education in the United States express an urgency to increase both the quality of the learning experiences created by colleges and universities and the number and diversity of well-prepared graduates with STEM degrees (President’s Council of Advisors on Science and Technology (PCAST), 2012). The social and economic success of modern democratic societies is seen as tightly linked to the preparation of a diverse technical workforce. Many calls for improving undergraduate STEM education rely on results from DBER to support their arguments and to provide guidance on how to implement and evaluate reform efforts. The push for educational reform that relies on “evidence-based” instructional models and strategies is loud and clear, to the point that highly respected journals in science research, such as Science (e.g., Ruiz-Primo et al., 2011) and Proceedings from the National Academy of Science (e.g., Freeman et al., 2014), have opened spaces for the publication of DBER studies that provide evidence of the educational gains associated with research-based teaching methods. The call for using research findings to guide educational reform at the post-secondary level is also evident in the recent National Research Council’s (NRC) report on DBER (NRC, 2012a), and in the various editorials and commentaries that this NRC publication has spurred (Cooper, 2014; D’Avanzo, 2013; Singer, 2013).

The gains in scope, depth, visibility, and attention that DBER has experienced in recent years create opportunities and challenges that should be carefully analyzed. The future of DBER programs and efforts across universities in the United States strongly depends on the quality of the research that is carried out, the extent to which such research targets critical areas for the advancement of STEM education at the post-secondary level, and the success in translating research findings into teaching practices that improve diverse students’ learning and achievement. To a great extent, the papers included in this special issue highlight important issues that should be present in the mind of DBER scholars as they define and reflect on the best path forward. Many of the articles illustrate the power of collaborative research efforts that advance our understanding in critical areas, such as conceptual integration across traditional disciplinary boundaries, development of authentic expertise, learning and teaching of diverse students, and translating research into effective practice.

Challenges and Opportunities

Collaboration

The NRC’s report on DBER (NRC, 2012a), and the several papers commissioned during the development of this document (NRC, 2012b), present a detailed picture of the history and current status of different DBER fields in the United States. These documents highlight similarities and differences, as well as strengths and weaknesses in a variety of areas, from graduate training programs to avenues for dissemination of results to academic recognition of DBER work and scholars. In general, DBER faculty seem to share core research goals and interests, and their work is subject to similar constraints in their different home departments and institutions. Many of them have received their graduate training in science departments, where they also tend to hold faculty positions, and have explored similar aspects of learning and teaching in their disciplines such as students’ conceptual understanding, problem-solving abilities, and representational competence. Despite these similarities, DBER can be characterized as a somewhat segregated enterprise comprised of several subfields with sharp boundaries and limited direct interactions. Researchers in each subfield tend to communicate their work in specialized journals and conferences that are
mostly geared toward members of that same research community (e.g., chemistry education research, physics education research). Unfortunately, collaborative research efforts are not common, neither in the form of collaborations involving DBER scholars in different science departments nor in the form of teams comprised of DBER scholars and researchers traditionally placed in Colleges of Education (e.g., science education, educational psychology).

Breaking or crossing boundaries within and beyond DBER is one of the major challenges faced by researchers in this area. Efforts in that direction are underway (Manthey & Brewe, 2013; Redish & Cooke, 2013), but they need to be widen, strengthen, and multiplied. The current lack of interaction and cross-fertilization between different subfields limits the depth and potential impact of everyone’s research. It leads to unproductive repetition of research studies that add little insight to our understanding of core learning and teaching issues, and to research frameworks that are mostly applied by members of a single community. Without ignoring important differences in the nature of the core concepts and ideas targeted by each discipline, as well as in the educational practices and traditions in each subfield, DBER scholars would benefit from acknowledging the many critical issues that they have in common and making more productive use of existing conceptual frameworks and methodological approaches that are useful in answering the research questions that they pose. They would also benefit by being more open to learning from and collaborating with experts working outside the disciplines, in education, psychology, and the cognitive and learning sciences. All these different collaborations are not only likely to improve the quality and diversity of DBER but also create the types of interactions that can promote and sustain wide systemic educational reform at the post-secondary level.

Three papers in this special issue are examples of studies that broke disciplinary boundaries and involved productive collaborations between DBER scholars and researchers in other fields. For example, the study by Varma-Nelson and collaborators (Article #2) involved chemistry education researchers and educational psychologists in the investigation of the comparative effects of two different learning environments, face-to-face versus online peer-led team learning workshops in freshman general chemistry. These authors generated an in-depth analysis of the effects of each type of workshop by engaging in discourse analysis, looking for instances of high-level student engagement in collaborative work. Similarly, in the study by Lopez et al. (Article #3), chemistry education researchers collaborated with specialists in educational assessment to explore the knowledge structures of organic chemistry students with ethnically diverse backgrounds. In that contribution, the authors applied tested assessment strategies based on concept mapping to explore the effects of student achievement and ethnicity on knowledge structure. Finally, in the work by Novick, Schreiber, and Catley (Article #4), psychology and biology education researchers studied the learning impact of an instructional booklet designed to improve student understanding and productive use of evolutionary trees. The curricular and assessment materials developed as part of this educational intervention resulted from the careful integration of disciplinary content analysis, knowledge of students’ conceptual difficulties in the field, and research from educational and cognitive psychology on how people learn. These three studies illustrate the analytical depth that can be gained by combining the expertise of researchers in different fields.

Conceptual Integration

Collaborations between DBER scholars in different disciplines are also needed to develop research projects and programs that look at educational issues that cut across various subfields. The comprehension of many disciplinary core ideas in the sciences demands the understanding of crosscutting concepts such as energy, equilibrium, and variability, and the application of science practices, such as modeling and argumentation (NRC, 2012c). In many cases, these types of
concepts and practices are interpreted, represented, talked about, and applied in different ways in the various STEM disciplines, and students are left to reconcile these different conceptualizations on their own. In recent years, several researchers have acknowledged this issue and begun working with colleagues in other fields to explore the challenges that students and instructors face in bridging different disciplinary perspectives about overarching concepts and practices, in order to build integrated understandings (Cooper & Klymkowsky, 2013; Redish & Cooke, 2013). Research that provides insights into how to foster and best support such a conceptual integration is sorely needed and can only result from the active collaboration of DBER specialists. Results from this type of research could spur discussions about curricular and assessment reforms at the college level that transgress conventional disciplinary boundaries. It could also provide insights into differences and similarities in ways of inquiring and building arguments and explanations in the different disciplines (Coppola & Krajcik, 2013). This is the type of research that can open the door to needed conversations about how to build robust interdisciplinary programs at the college level.

A first step on the path to understanding how to best achieve conceptual integration of crosscutting concepts and science practices demands the analysis of how such concepts and abilities are represented and interpreted in the various disciplines. This type of work requires careful reflection about how specific concepts and practices are used to build explanations and make predictions in a given field, and detailed exploration of how students think about and apply them when working on relevant disciplinary tasks. The contribution of Becker and Cooper in this special issue (Article #5) is illustrative of this latter type of work. In particular, these authors explored college chemistry students’ understanding of potential energy in atomic-molecular interactions of chemical importance (e.g., bond formation). Their results elicited three common ways of conceptualizing potential energy in chemistry contexts: as capability, as stored energy, and as related to stability. Some of these ways of talking about energy are similar to those reported by education researchers working in physics contexts (Scherr, Close, McKagan, & Vokos, 2012). However, more research is needed to determine the degree to which some of these conceptualizations are productive in fostering conceptual integration of the targeted concept within and across different disciplines, and in designing curricula and instructional strategies that best promote such integration.

Development of Expertise

A central goal of post-secondary STEM education is to prepare individuals with specialized knowledge and skills ready to join the workforce. It is thus critical for DBER scholars to understand both the nature and development of expertise in their disciplines. These tasks are not straightforward because what many people conceive as expert knowledge and behaviors in academic settings may differ from actual manifestations of expertise in authentic work environments (e.g., industry, research labs). Existing research in this area has mostly focused on the characterization of progressions toward normative understandings in a given area, without much analysis of how and to what extent those normative understandings are actually used by practitioners when solving authentic problems. These latter types of investigations are needed to design studies that characterize how professional expertise develops, how to better foster such progression, and how to support educational reform efforts that are guided by authentic performance expectations rather than by traditional conceptualizations of what it means to master the subject matter.

The contribution of Bhattacharyya and Bodner in this special issue (Article #1) represents a good example of the types of investigations that can provide insights into the development of authentic expertise. In that paper, the authors focused on the identification and characterization of the types of tasks that support epistemic development from graduate student to practitioner in synthetic organic chemistry. As described in the article, the transformation of students’ epistemic
framing of course and curricular tasks was strongly influenced by their perceptions of the “authenticity” of such activities, and by the feedback received from more-knowledgeable others when engaged in such tasks. These findings pose a major challenge to STEM education reform efforts as they point to the need to create learning environments in which students engage in authentic activity guided by frequent, significant, and meaningful formative assessment. How to create such learning spaces in college courses involving large numbers of students deserves in-depth exploration.

Diversity

One of the major challenges of STEM reform is the creation of learning opportunities that are meaningful and productive to a wide range of students. Acknowledging and understanding the effect that factors such as gender, ethnicity, cultural background, socioeconomic background, and prior academic performance may have on students’ readiness and disposition to learn is critical to reducing existing gaps in enrollment, retention, and achievement among different student populations. Research studies that are purposely designed to explore relevant differences and similarities among different groups of students, or that allow the disaggregation of data to analyze differential effects of educational interventions are thus needed to advance the STEM reform agenda at the post-secondary level (Lopez, Nandagopal, Shavelson, Szu, & Penn, 2013). Again, collaborations between DBER scholars and experts in multicultural education should be forged to enrich the conceptual frameworks guiding such investigations, strengthen research designs, and deepen data analyses.

Three of the contributions to this special issue on post-secondary science education research consider issues of student diversity and provide insights into how different factors affect, or not, student learning and performance in different settings. In fact, this type of analysis is at the core of the work presented in Article #3 by Lopez and collaborators. In this study, the authors sought to explore the potential effect of ethnicity on students’ knowledge structures in organic chemistry. Although core findings reveal significant differences in performance among different groups of students, such differences seem to more strongly correlate with overall academic achievement (as measured by students’ GPA) than with ethnicity. This work clearly illustrates the challenges that researchers face in disentangling the effect of variables that are likely coupled in educational environments (e.g., ethnicity, socioeconomic background, and academic performance). Issues of diversity are also analyzed by Varma-Nelson and collaborators in Article #2, where the authors report that students from underrepresented minorities and lower socioeconomic status who participated in online peer-led team learning workshops were more likely to receive D or F grades, or to withdraw from the course, than similar students who enrolled in face-to-face versions of the workshop. Although further investigations are needed to understand what factors may be responsible for this outcome, the findings highlight the importance of exploring differences in performance of diverse types of students working in alternative educational settings. Finally, in Article #4, Novick and collaborators explored the differential effect of their instructional intervention on students with stronger versus weaker content backgrounds in biology. In this case, the authors found equivalent gains in tree-thinking skills for both groups of learners. These results confirm the finding that educational resources designed through careful analysis of and reflection on targeted scientific ideas, students’ learning difficulties, and evidence-based pedagogical practices are likely to benefit learners with diverse educational backgrounds.

Translation into Practice

For many, the crux of DBER is how to translate research results into practice (NRC, 2012a). Although still scarce in several critical areas, particularly at the advanced post-secondary levels,
studies on the conceptual difficulties that students have in understanding disciplinary core ideas and crosscutting concepts in STEM disciplines, or in solving core disciplinary problems and tasks, have provided insights into how to better scaffold student learning. Similarly, investigations on diverse instructional approaches such as project-based learning, model-based learning, and guided-inquiry have elicited the educational benefits of, for example, collaborative group work, model building and evaluation, and generating arguments and explanations (Ruiz-Primo et al., 2011). Still, more research is needed to determine how to best integrate these understandings and practices into the design, implementation, and evaluation of curricula, instructional methods, and assessments that result in meaningful learning of specific core ideas in a given discipline, development of valued skills, or significant changes in attitudes and beliefs of targeted populations. This research demands the development of valid and reliable instruments and strategies to measure educational outcomes beyond final test scores or retention rates. It also requires the application of research methods that generate data that not only tell us what changes occur, but how they occur and what mechanisms underpin the observed changes. These are areas in which collaboration between DBER scholars and experts in other fields (e.g., assessment and measurement) would be highly beneficial.

Two studies included in this special issue investigate the outcomes of educational approaches that were designed taking into consideration existing research findings on both how people learn and best teaching practices. In the case of Article #2, the authors relied on a variety of data sources to evaluate the effects of two modalities of peer-led team learning on participants’ learning and attitudes. In particular, analyses of the teams’ dialogues throughout the different workshop sessions allowed the authors to identify differences and similarities in students’ social interactions, depth of content discussions, and pedagogical practices implemented by team leaders working either face-to-face or online. This level of analysis elicited how specific characteristics of each learning environment influenced student-student and student-peer leader interactions. The authors of Article #4 used a carefully designed assessment instrument to evaluate the effect of their intervention on students’ mastery of core thinking skills about phylogenetic trees, such as determining relative evolutionary relatedness, identifying clades, and making inferences based on shared ancestry. Although the research methods applied in this study did not elicit which particular aspects of the intervention led to particular outcomes, the design of the assessment created opportunities for analyzing the effect of using the designed instructional booklet on each of the targeted tree-thinking skills.

Missing Pieces

The five papers selected for this special issue on post-secondary science education research summarize the findings of studies that advance our understanding in two main areas, (i) students’ conceptual understanding of disciplinary core ideas and crosscutting concepts (Articles #3 and #5), and (ii) effect of research-based instructional interventions on students’ understanding and achievement (Articles #2 and #4). These have traditionally been the two most dominant areas of research in DBER and they are likely the fields in which research in undergraduate STEM education has reached greatest maturity. Article #1 in the series has a different focus as it describes a study on the development of epistemological understanding in a discipline. Although several DBER authors have explored college students’ epistemological understanding in areas such as chemistry (Mazzarone & Grove, 2013) and physics (Redish, Saul, & Steinberg, 1998), this in a topic of research that is still wide open for further investigation. The strong attention that DBER scholars have paid to the analysis of the nature and development of students’ conceptual understanding is comprehensible for various reasons. Researchers in post-secondary STEM education tend to be disciplinary experts with strong interests in the development of students’
content knowledge. Traditionally, undergraduate preparation has focused on mastery of the subject matter. And, overall, research on conceptual issues has also been dominant in STEM education at all grade levels in the past 40 years. Nevertheless, we should recognize that in order to advance the research agenda and strengthen educational reform in STEM fields we need to widen the scope of our investigations, not only in terms of research topics, but also in relation to the nature of the learning spaces under analysis and the types of participants involved in our explorations.

Although the field of research on student learning is vast, I would like to highlight some areas of investigation that are underrepresented in existing DBER studies that are critical for advancing STEM educational reform:

(1) We need to deepen our analysis of the nature and development of reasoning in science and engineering, in particular model-based reasoning (Magnani et al., 1999) and mechanistic reasoning (Russ, Scherr, Hammer, & Mikeska, 2008). There is evidence that suggests that meaningful understanding of core concepts and ideas in the sciences is fostered by engaging students in the development of mechanistic accounts of phenomena by using, creating, testing, and evaluating models of the systems of interest (NRC, 2012c; Windschitl, Thompson, & Braaten, 2008). Our understanding of how college students engage in these types of practices is rather limited, particularly when working with complex systems whose analysis requires the integration of different types of knowledge.

(2) We ought to investigate the nature and development of metacognitive knowledge and skills, which are critical for the tactical and productive deployment of scientific reasoning. Research indicates that experts in a field not only possess a highly integrated knowledge structure, but highly developed metacognitive knowledge that allows them to tactically apply and control their reasoning (Sternberg, 1998). There is a small number of studies that provide insights into how to assess and foster the development of metacognition at the post-secondary level (Cooper, Sandi-Urena, & Stevens, 2008; Vander Stoep, Pintrich, & Fagerlin, 1996).

(3) We need to explore how sociopsychological issues influence the learning outcomes for diverse populations of students at the post-secondary level. In particular, students’ knowledge, beliefs, and perceptions about themselves in academic achievement situations (academic self-concept) and their convictions about their ability to successfully perform academic tasks (academic self-efficacy) have been shown to enhance or impair academic performance through their effect on cognitive, affective, or motivational processes (Aguilar, Walton, & Wieman, 2014; Ferla, Valcke, & Cai, 2009).

(4) Attention to student learning at the post-secondary level also needs to expand to more thoroughly investigate what is happening outside the classroom or beyond the confines of paper-based academic tasks. This certainly includes investigations focused on the affordances and constraints of new information and communication technologies for learning and instruction, as explored in the work by Varma-Nelson and collaborators in this special issue (Article #2). Perhaps a more urgent need is to deepen our understanding of meaningful learning and productive teaching practices in laboratory and fieldwork settings. Science departments invest large amounts of human and capital resources in the experimental or experiential components of their academic programs with little evidence of significant positive effects on student learning (Matz, Rothman, Krajcik, & Banaszak Holl, 2012). The limited research on the efficacy of inquiry-based approaches and research experiences in undergraduate science education has generated mixed results, in a large part due to the structural and programmatic constraints in which these experiences tend to take place (Reid & Sha, 2007). Significant reform in STEM education demands a more systematic and comprehensive investigation of what is happening in undergraduate laboratories and of new models for lab-based education.

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Most of DBER studies published to date have centered their attention on the analysis of student knowledge, beliefs, or attitudes and on the effect of different instructional approaches on some aspect of student cognition or motivation. Fewer investigations have focused on the analysis of instructor knowledge, thinking, and learning (Henderson & Dancy, 2007). The causes for this imbalance are likely multiple. College instructors in STEM areas are experts in their fields and their content knowledge is seldom questioned or explored. Most of them do not receive formal teaching preparation and their knowledge and beliefs about teaching are shaped by personal experiences and professional expectations in their field. Many instructors at the post-secondary level rely on lecturing as their main teaching strategy and their knowledge and beliefs about teaching are perceived as narrow, monolithic, and thus highly predictable and resistant to change. However, the calls for broad and deep reform in STEM education create a need for better understanding these types of practitioners in order to forge professional development programs that meaningfully affect their teaching knowledge, beliefs, and practices and align them with those informed by DBER. The need for more research on effective models of STEM faculty preparation and development on teaching is urgent in order to effectively transform undergraduate education (Henderson, 2008; Vergara et al., 2014). In particular, we need to better understand the nature of college instructors’ pedagogical content knowledge and explore effective strategies to scaffold and develop it; research in this area is rather scarce (Major & Palmer, 2006; Padilla, Ponce-de-León, Rembado, & Garritz, 2008). Beliefs about the primacy of content knowledge over any other forms of teacher knowledge in higher education need to be tested by more carefully analyzing the relationship between faculty knowledge and student learning (Abell, 2007). All of these types of studies should be carried out in parallel with investigations that more broadly explore the types of reforms that need to be implemented to support culture change in educational practices at the course, departmental, and institutional levels (Henderson, Beach, & Finkelstein, 2011; Kezar, 2009). These latter research efforts are likely to be more effective and productive if they involve the collaboration of DBER scholars, college faculty and instructors, administrators, and researchers with expertise in higher education and in organizational change.

Final Remarks

The transformation that is needed in post-secondary STEM education to respond to the national needs for a highly qualified technical workforce is significant (PCAST, 2012). The reform will not only demand the reconceptualization of curricular, instructional, and assessment practices but also the enrichments and transformation of the knowledge, beliefs, attitudes, and behaviors of students, instructors, and administrators. The task seems daunting given the organizational structures, cultural norms and practices, and implicit and explicit expectations that are common in many of colleges and universities. Reform efforts can be expected to be particularly challenging in research intensive institutions in which organizational history, academic hierarchies, professional incentives, and rewards systems favor research over teaching, and put decision-making in the hands of STEM research faculty who are not necessarily prepared or motivated to implement educational change (Fairweather, 2008).

Nevertheless, external pressure to enact change is mounting and DBER scholars are finding themselves at the front of the reform movement. The knowledge base that has been built in over 30 years of DBER provides solid ground to create blueprints of what is required to plow forward. But considerable work still needs to be done. There is a need to diversify the nature of the research, strengthen research methods, and deepen analyses. Besides generating evidence of what students do not know or are unable to do after completing traditional STEM courses, or about “what works” in education, with the expectation of changing instructors’ teaching beliefs and practices, we should ramp up our efforts to better understand how learning actually happens and how and why
particular interventions are more successful than others at helping diverse students progress in their understanding. We should find a balance between the need for practical and effective solutions to our immediate educational problems, and the development of knowledge that can help us move students beyond the confines of traditional views of mastery and achievement in current post-secondary STEM education. It is not longer enough to demonstrate that evidenced-based teaching practices help students better achieve traditional learning objectives; we should challenge those objectives and demonstrate that higher-level and more authentic performance expectations can be pursued and attained.

DBER scholars should also face and embrace the challenge of studying and fostering faculty professional development within the major constraints imposed by current structures and practices in institutions of higher education. We should design, test, and evaluate avenues for creating and sustaining institutional cultures that expect and support ambitious teaching practices, that is “teaching that aims to teach all kinds of students to not only know academic subjects but also be able to use what they know in working on authentic problems in academic domains” (Lampert, Boerst, & Graziani, 2011). This type of work cannot be completed in isolation and will require maximizing and leveraging relationships with multiple stakeholders in the STEM education reform process. It will likely require intense ground work in multiple STEM departments within a single institution and the formation of coalitions across multiple departments and universities. Some of these efforts are already under way; we need to intensify and multiply them.

References


