FEATURE ARTICLE

Considering Grand Challenges in Biology Education: Rationales and Proposals for Future Investigations to Guide Instruction and Enhance Student Understanding in the Life Sciences

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Abstract

An international group of biology education researchers offer their views on areas of scholarship that might positively impact our understanding of teaching and learning in biology and potentially inform practices in biology and life science instruction. This article contains a series of essays on topics that include a framework for biology education research, considerations in the preparation of biology teachers, increasing accessibility to biology for all learners, the role and challenges of language in biology teaching, sociocultural issues in biology instruction, and assisting students in coping with scientific innovations. These contributions are framed by a discussion of the value of defining several potential "grand challenges" in biology education.

Key Words: *biology education research; teacher education; learning biology; language; sociocultural contexts and instruction.*

○ Introduction

It should be clear to anyone aware of the sheer volume of articles produced annually that the educational research enterprise is thriving. Each year increasing numbers of researchers enter the field and collectively add to the enormous numbers of papers on all facets of education. Although we are awash in a sea of education publications and data, this wave of studies, opinions, and recommendations have done little to change the daily practices of teachers or result in enhanced learning outcomes in truly fundamental ways. The purpose of this paper is to make the case that the biology education research community must establish a shared framework to help reveal important unresolved issues and work together toward their resolution and impact on classroom practice as a result. To that end, the group of experts featured in this article came together to discuss the issue and offer some initial insights.

> *So, perhaps we might call these suggestions emerging Grand Challenges in Biology Education and offer them for consideration of where future research work in biology instruction might be focused.*

To begin, we should discuss some of the challenges associated with education research generally. First, there is the unsettling conclusion that we most certainly have challenges with dissemination and perceived relevance. The results of our research are largely unknown to policymakers, teacher educators, administrators, and most importantly, teachers—who are really the only individuals in a position to apply research results. Sadly, much education research is ignored by teachers, who sometimes falsely consider that studies not conducted in schools exactly like theirs would not pertain to them. Another reason why much educational research is ignored is that the studies often have low numbers of subjects, produce non-generalizable results, and were never of much interest to those in the community of practice. It is understandable that the demands on teachers are so severe that one would question how educators would find the time and resources to read, assimilate and put into action even those recommendations that seem promising. Also, much education research is available only in expensive journals written in ways that fail to offer explicit practical applications.

Clearly, within education research generally and science education specifically, we must take some responsibility for our own marginalization. How many among us, when beginning a new project, ask the question, "So, what important question can I attack next that educators really need to have addressed?" Rather, we often work on small projects of personal interest with little consideration for the importance to practitioners of the underlying questions or the ways in which the results will be disseminated to impact practice. We share our results primarily with each other at *our* meetings and in *our* journals with little regard for practice. To validate this point, examine the titles in any research publication to see how many share

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results from potentially important avenues of investigation with large enough sample sizes and diversity to make generalization possible. Certainly, there is nothing wrong with conducting "pure" or exploratory research in education, as we occasionally do in science itself. However, some consideration of the need for a given line of research and its potential applicability to practice must be part of the research rationale.

Despite this situation, perhaps there is another approach for us in biology education. The special issue of the journal *Science* (April 19, 2013) called for a consideration of *Science Education Grand Challenges* potentially to guide research in addressing large problems in science learning. Some of the Grand Challenges articulated in the article included the proper role for technology, an understanding of how individual differences in brain development impact learning and professional development for teachers, and what skills are necessary for teachers to implement high-quality laboratory teaching. Additional challenges identified include establishing personal relevance for learners and developing students' understanding of how science creates knowledge, along with a suite of suggestions about how teachers can engage in research at the school level and how assessment results might guide instruction. The idea of Grand Challenges is important, but questions remain about who will assume the responsibility for conducting the research necessary to explore these challenges, and the best way to share results with those who might take appropriate action.

Thinking about Grand Challenges in Biology Education

The challenges discussed in the special issue of *Science* are worthy of consideration, but as Zogza (2016) reminds us, biology education, or "biology didactics" as it is sometimes called,[1] is a unique discipline with special teaching and learning contexts. Biology education research therefore must be "aimed at highlighting and facilitating the process of teaching and learning about the biological world" (p. 181) specifically. We can and should consider and build on research in science education generally, but there are problems and challenges that are unique to biology teaching and learning. It is reasonable to consider that all the Grand Challenges in science education might be explored through the lens of their implications to biology instruction, but it is likely that biology didactics will have its own set of issues worthy of focused exploration.

In past decades, many researchers have investigated programs in biology teaching and learning, published their results in prestigious journals, and occasionally offered teaching suggestions stemming from those investigations. Groups that focus on biology education regularly endeavor to improve teaching and learning in this domain, but rarely have there been focused attempts to identify the big issues on which the research community should focus its energies. Even less frequently do we see a team approach to address big programs in this domain. One group that has accepted some of the burden of focusing research on problems in biology instruction is the European Researchers in Didactics of Biology (ERIDOB), which dedicated its tenth conference in June of 2014 in Haifa, Israel, to *The Future of Biology Education Research*. This important question was revisited in September 2017 with a panel discussion at the eleventh conference in Karlstad, Sweden, resulting in this paper.

Of course, we are not suggesting that this article provides a definitive list of the problems most worthy of investigation; that task will have to wait until a larger and fully representative group of scholars is convened for the purpose of suggesting additional avenues of future research. However, those of us who gathered recently are pleased to offer some potentially interesting thoughts about necessary research on topics such as teacher education, the role of language, sociocultural issues, socioscientific considerations, and other notions as they relate to biology instruction. So, perhaps we might call these suggestions *emerging* Grand Challenges in Biology Education and offer them for consideration of where future research work in biology instruction might be focused.

We begin with thoughts about a framework for such research that looks across the three domains: biology, education, and the research enterprise itself. The suggestions that comprise the bulk of this article are contributed by a group of international scholars each with their own areas of specialization, who were asked to provide some background in a specific area of investigation and then offer specific questions or areas of research based on their unique domain of interest. Again, we do not claim to have listed all areas of necessary future research, but trust that readers will find these suggestions compelling nonetheless.

○ A Proposed Framework for Biology Education Research

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There are several possible frameworks that might guide biology education research. One approach is to see such research as the point of intersection of three overlapping domains—biology, education, and research—as they relate in a Venn diagram-like fashion (Reiss, 2016).

If we start with **biology**, we might take an approach that derives from Hirst's (1965) "forms of knowledge," focusing on the distinctiveness of biology itself. For a start, biology sits within the natural sciences, which have a methodology that emphasizes knowledge as objective, universal, and amenable to rational inquiry. Within the natural sciences, biology, of course, is the study of life. In a sense, our choice of subjects is vast because there are perhaps ten million extant species, each of which could be investigated in several ways. The most important biology research often proceeds by studying a range of species, which then permits making conclusions or constructing new models that are both widely applicable and amenable to such local variation. This approach is widely demonstrated in the work of Darwin, Mendel, the discoverers of the structure of DNA, and ecologists such as E. O. Wilson. There is a lesson here for biology education research: we surely want to engage in fine-grained research that is true to the particularities of a situation; we also want to be able to extrapolate to broader horizons.

If we start with **education**, then we begin with what has been described not as a single discipline (like history, mathematics, or biology itself) but a field. Like medicine and engineering, education draws on a wide range of fundamental disciplines (e.g., psychology, sociology, and philosophy) to make its advances. This approach makes an epistemological point about knowledge production in education.

However, another way of starting is not from an epistemological standpoint, but from a normative one related to values and what students, teachers, and society generally *want* from a good education. It has been argued that there are two fundamental aims of education: to equip each learner to lead a life that is personally flourishing; and to help others to do so, too (Reiss & White, 2013). In this approach, biology education research contributes to such flourishing. Indeed, if "others" is understood to include non-humans, this argument can be seen as manifesting an inclusive environmental education. At present, this argument for the fundamental aims of education seems powerful. We are so used to arguments about extinctions, climate change, and other threats to our continued existence that it can be difficult to keep in mind how exceptional, from a biological perspective, is the age in which we live. Indeed, the recent coining of the term "Anthropocene" is an attempt to remind us of this very fact and how unusual are the current times, when seen from an historical perspective.

We have deliberately started with biology and education because, along with many who would read this article, our shared experience when supervising doctoral students and researchers is that such individuals often start with **research**. To be sure, that is yet another way to begin. Researchers are expected to identify a gap in the literature, formulate research questions, then derive a methodology to address these questions. Although such an approach adds to the literature, such findings are unduly constrained by the accidents of history—since what has previously been investigated drives the identification of gaps in the literature, and thus our own research. A better starting point is to combine the personal interests of researcher(s) with analysis of what *ought* to be researched. We need to keep in mind the purpose of our research, i.e., what is needed, as argued by Steinberg and Kincheloe (2004), who encourage researchers to ask research questions that will make a difference in students' lives. Or, as Karl Marx said, "The point is not merely to understand the world, but to change it," but it is important to add that this change should be evaluatated from as many perspectives as possible.

As you see in the contributions from my colleagues elsewhere in this article, we have endeavored to suggest some of the areas in which biology education research might make such a contribution—whether in the education of the next generation of biology teachers, determining how to teach biology, increasing accessiblity of biology to all learners, ensuring that biology is taught authentically, or in many other ways. Our shared hope is that biology education research can indeed make an increasingly valuable contribution to what needs to be done for the benefits of learners, for human society generally, and for the planet as a whole.

○ The Nature of Teacher Education Programs in Producing Informed and Effective Biology Teachers

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Among the many factors impacting effective learning of biology, few are as important as the nature of the biology teacher. Teachers are the intermediaries between the content and processes of biology and the students themselves; biology teachers must be both informed and effective. Therefore, a major future research goal is to define optimal teacher education programs that can produce and develop informed, effective, and empathetic biology instructors. The topic is conceptualized in relation to preservice teacher education although answers may apply equally to in-service teacher education.

A variety of proposed research questions relate to the preparation of biology teachers. Such key questions are related to the following domains:

Determining the Qualities of an Effective Biology teacher

The qualities of an effective biology teacher, once identified, must inform the structure of preservice teacher education programs. Lederman and Lederman (2015) reviewed the history of attempts to determine the qualities of a good teacher and describe a transition from originally asking the opinions of students to engaging the opinions of experts later. However, opinions about effectiveness of science teachers are context-dependent. For example, students, peers, administrators, and parents all will have different perspectives on what makes a biology teacher good. An educational system that is strongly examination-oriented may judge an effective teacher to be one whose students perform very well in those examinations. By contrast, a schooling system that aims to produce critical thinkers will judge a successful biology teacher differently.

Knowledge and Skills of Effective Biology Teachers

From the early 1900s to the 1930s, effective teachers were described by several general attributes, including good judgement, magnetism, considerateness, and leadership (Lederman & Lederman, 2015). Later, an effective teacher was considered to be one who developed critical thinking skills and tolerance of a diversity of viewpoints and opinions (Lederman & Lederman, 2016). Matthews (2015) describes a good teacher as a person who knows the subject, is interested in children and teaching, can use technology effectively, and teaches engagingly.

One quality frequently identified with biology teaching effectiveness is their breadth and depth of subject matter knowledge. A Norwegian colleague, Peter van Marion, who has considerable experience in teaching the didactics of biology, in a conversation with me (February 2016) reports that his preservice students identified strong subject knowledge, commitment, and enthusiasm as the most important qualities of a good teacher.

The examples here support the conclusion that there are many answers to questions related to identifying the knowledge and skills of effective biology teachers. Additional research in this area would be productive.

Preservice Biology Teacher Education

Lederman and Lederman (2015) point out that there is no single best way to educate future science teachers. Matthews (2015) concurs, referring to countries that require no or minimal preservice teacher education. Simultaneously, some developed countries require a minimum of a Masters' degree in biology in order to teach at the secondary level. Contextual and political issues in different countries will impact decisions about the structure of teacher education.

It is useful to be reminded of the important and oft-cited work of Lee Shulman (1987), who proposed a framework for teacher education that identified three major components: subject matter knowledge (SMK), general pedagogical knowledge (PK), and pedagogical content knowledge (PCK). These three components were subsequently expanded to include knowledge of the curriculum, knowledge of students, and contextual knowledge.

SMK is defined as a deep understanding of the fundamental concepts of a subject, knowledge of the research methods of that discipline, and knowledge of the nature of science (Groβschedl et al., 2015). Studies have shown that SMK alone is insufficient for effective teaching, hence the necessity for PCK (Zeidler, 2002; Groβschedl et al., 2015). PCK is knowledge of what makes subject matter comprehensible to students (Groβschedl et al., 2015). PK includes the foundation education disciplines such as philosophy, sociology, history, and psychology of education.

Zeidler (2002) argues for a model of preservice teacher education that integrates SMK, PCK, and PK. He states that philosophical incompatibility between science faculty and education faculty preclude the possibility of achieving integration if teacher education is co-located with science instruction. In other words, Zeidler appears to argue against a science-content-only focus in preservice science teacher education. Others disagree. For example, Groβschedl et al. (2015) found a positive relationship between the SMK and PCK of preservice biology teachers, in a program where SMK was developed in the science department. Their study did not address the question of whether good SMK and PCK scores translated into effective classroom teaching. Zeidler (2002) and Groβschedl et al. (2015) agree that SMK, PK, and PCK must be included in teacher education programs.

Considering Different Models of Teacher Preparation

As Matthews (2015) has pointed out, there is little agreement among and within countries about how best to educate science teachers. For instance, South Africa currently offers two models of teacher education, both qualifying teachers to teach biology at the senior secondary level. One model is a general three-year Bachelor of Science (B.Sc.) degree followed by a Postgraduate Certificate in Education (PGCE). The second model is a four-year Bachelor of Education (B.Ed.) degree. In the B.Sc. + postgraduate certificate training model, SMK is developed in the Faculty of Science, and students have no exposure to PCK or PK until they reach the PGCE. In the B.Ed. model, SMK, PCK, and PK are taught simultaneously in the Faculty of Education.

In the United States, students with degrees in biology are increasingly encouraged to skip traditional teacher preparation, take a few summer seminars, and move directly to the classroom. A similar trend is evident in the United Kingdom, where the government encourages graduates to move directly into schools, where they undergo an apprenticeship mode of training (Matthews, 2015). It remains to be seen whether this produces effective teachers or just more individuals who serve briefly in teaching roles.

With such diversity of preservice programs in operation worldwide, there is ample scope for research on the relative effectiveness of different programs for biology teacher preparation. Such research will provide evidence that informs decision makers about the structure of preservice teacher education. Clearly, there is much work to be done in the field of research into effective and efficient biology teacher preparation.

A summary of potentially fruitful avenues for research in biology teacher education includes:

- Identification of criteria for evaluating teaching effectiveness.
- Identification of the necessary knowledge and skills related to teaching effectiveness within different contexts and from different stakeholders' perspectives. In turn, the answer to this quest should inform the design of both preservice teacher education and in-service teacher development.
- Determination of the form each of these components takes, and how much of each component (SMK, PCK, and PK) makes an effective biology teacher.
- Evaluation of a program of teacher education must include evaluation of the classroom effectiveness of the teachers it produces. Such research will provide useful evidence informing the curriculum for preservice teacher education.

○ Theoretical and Practical Approaches to Make Biology Accessible to All Learners

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Making biology education accessible is a daunting quest. Challenges in teaching and learning biology have been studied extensively in terms of the topics that students regard as difficult. Students' interest in biology in general along with gender- and age-related differences in interest, and students' understanding of the structure of the discipline have also been investigated. Additional underlying factors that may contribute to learning difficulties include the complications related to levels of organization and the abstract concepts involved (Lazarowitz and Penso, 1992). We must attend to the amount of content that students may find overwhelming and difficult (Çimer, 2012), and the complicating factors associated with the requirement that students must switch thought levels from tangible to molecular to symbolic or mathematical (i.e., in genetics) (Bahar et al., 1999). Further impediments in learning biology also include students' interest in learning specific content. The Relevance of Science Education or ROSE Project (roseproject.no) has revealed a lack of interest in biology topics particularly among males in developed countries (Sjøberg and Schreiner, 2010), thus suggesting a gender and cultural gap in biology learning. Students' interest in biology also appears to diminish with age (Prokop et al., 2007), which may be linked to a perception of biology as a difficult subject (Çimer, 2012). Finally, we must content with students' prior familiarity and potential alternative understanding of biology concepts.

All these difficulties suggest a need to rethink biology education. This reconsideration might be characterized from three perspectives: epistemological, metacognitive, and motivational. *Epistemologically*, if we accept biology learning as a personal construction rather than a transmission process, and if we hope that students will "own" the knowledge acquired, more active student-centered learning approaches should be considered. At the same time, a more student-centered approach must account for potential conflicts with teachers' beliefs in a more traditional approach to teaching (Kinchin, 2001), such as the conception that teaching biology should be based on lectures (Subramaniam, 2014). Teachers' conceptions about biology and biology teaching are often intertwined with barriers such as time and resource constraints, which are necessary if they are to guide students through the knowledge construction process (Kinchin, 2001).

From a *metacognitive perspective*, research evidence shows that learning could be improved by encouraging students to reflect on how they learn and how effective their learning strategies are (Thomas, 2012). This would be helpful for students who perceive biology as difficult and hence lose interest. However, it is a tall order for teachers who are preoccupied with cognition rather than metacognition. Therefore:

The *motivational perspective* is also worth considering. Here different strategies have been suggested including out-of-school experiences such as farming and experience in science and technology (Uitto et al., 2006) and practical work and fieldwork, particularly for enhancing the interest of males (Prokop et al., 2007). However, one must not lose sight of the intricate relationship between the cognitive and motivational aspects. Hence, research studies would have to focus on both cognition and motivation at the same time.

An additional consideration in this research agenda: it would be difficult to envisage that any teaching or learning approach, no matter how promising it appears to be, can fit the needs of all students. Future research from the three perspectives discussed here should also address the differences across gender, age, ability level, and culture as informed by research findings to date.

Therefore, from the perspectives discussed here, several future research questions and approaches might be suggested to assist in breaking down barriers. These include:

- How may teachers be encouraged to reflect on their conceptions about teaching biology to bring them more in line with more active learning approaches based on constructivist learning?
- How can teachers use teaching approaches to guide students through the hierarchy of biological knowledge at various levels of organization.
- How can biology teacher educators most effectively model these teaching approaches in methods courses?
- How can beginning teachers be helped to reconcile the apparent conflict between student-centered approaches and school curriculum contexts that are not conducive to the implementation of these approaches?
- Research to establish the interaction between cognition and metacognition in the context of biology learning, and the teaching strategies for enhancing students' metacognition such as awareness and evaluation of their own learning processes.
- How can biology teachers can be encouraged to reflect on their beliefs about instruction and how those beliefs came into existence, what impact they have on teaching processes, and how these processes could be improved?
- Consideration of the merits or demerits of aligning biology education with two recent movements in science education—SSI (socio-scientific issue) education and STEM education—by using SSIs and engineering design, respectively, as contexts for promoting conceptual learning and scientific reasoning.

○ The Challenge of Developing Teachers' Pedagogical Knowledge with Respect to Language in Biology Education

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Investigations into the didactics of biology focus on questions like *what*, *how*, and *why* biology is taught and learned. The aim is to encourage the examination of unanswered questions related to the development of teachers' pedagogical knowledge. First, I will suggest reasons why we should do this, then mention some important and under-researched questions, and end by discussing how this might be accomplished through professional development.

Students' learning depends on many background factors such as the learners' social, cultural, and language background, but if the aim of schooling is to balance inequalities, research endeavors should investigate impacts from school itself, and that would logically center on the teacher factor, specifically on the skills possessed by teachers. Hattie (2012) reminds us that enhancing teacher competence is not rooted in increasing subject-matter knowledge, but instead on the ways that teachers introduce, organize, and scaffold learning experience related to biology content. In other words, teachers' pedagogical knowledge and competence should be targeted. This aligns nicely with how Shulman (1986, p. 13) describes professional teachers as those who are "capable not only of practicing and understanding his or her craft, but of communicating the reasons for professional decisions and actions to others." This implies that the quality of pedagogical knowledge is best perceived as *enacted* competence in classroom practice.

The Role of Language in Biology Instruction

When it comes to *what* kind of knowledge should therefore be developed, I suggest alignment with the idea "disciplinary literacy in biology," which means investigations that focus more on "content-based language teaching" (Dalton-Puffer, 2011), since learning biology involves learning to master and appropriate the specific language of school biology. Language in biology classrooms is a particularly challenging issue and is characterized by multimodality (e.g., representations, models, metaphors, formulas) and the use of specific words and semantic patterns (Lemke, 1990). According to Brown and Ryoo (2008), the combination of content and language components together enhance students' conceptual understanding.

Terms used in biology can be grouped in three categories: (a) biology-exclusive terms, (b) words found both in biology and elsewhere, but with different meanings, and (c) general language. Biology-exclusivity implies words only used in the science of biology (e.g., "allopatric," "genotype," and "stroma"). Understanding these concepts is important, and misunderstanding can block making meaning. Second, we have terms in biology that have other connotations in other contexts. Terms such as "adapt," "cycle," and "energy" can confuse learners since these terms have different meaning in everyday language. For example, students could arrive at school by "cycling," but in the biology classroom "cycling" is also associated with "life cycle" or the cycling of matter. Even the word "adapt" can be problematic; consider adaptation in evolution and in muscle function. The third group of expressions are general academic terms such as "converted," "proceeds," and "originates." These words must be understood in biology contexts or they can communicate meaning poorly. All three word-type categories of will cause problems for learners generally but are particularly troublesome for second-language speakers (Gibbons, 2003). Teacher must understand how language influences learning and develop strategies to enhance students' successful appreciation of appropriate scientific language on the continuum between daily and scientific use (Schleppegrell, 2016).

Hattie (2012) implies that research into these areas might occur in a collegial learning environment, leading to the proposal of "design research" agendas (Anderson & Shattuck, 2012) in which school-based teachers "own" authentic practice and engage in iterative cycles of planning, enactment, and evaluation of teaching and learning (for examples in genetics and nature of science, see Olander & Holmqvist, 2013; Holmqvist & Olander, 2017). This is not unlike the lesson-study model commonly used in Japan and frequently practiced elsewhere.

Research areas related to the language domain might involve the following:

- Determination of the specific character of language in biology classrooms.
- Research in applied linguistics to create a knowledge base related to content-specific vocabulary.
- "Design research" to explore questions related to the role of specific resources that may support and perhaps hinder learning.
- How achieving biological literacy is related to the language of biology.
- An examination of the ways that teachers can effectively scaffold students' learning progressions in biology by considering the continuum between everyday and scientific language contexts.

○ Three Possible Foundations for Research in Biology Education: Sociocultural Contexts; Consideration of Knowledge, Values, and Practices; and Didactic Transposition Delay

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In 2005, UNESCO proposed linking biology education with the promotion of fundamental values, such as human rights (i.e., gender equality and the struggle against racism, sexism, and homophobia) while encouraging environmental education for sustainable development, sex education, and health promotion. However, doing this in practice is a challenge. Increasing evidence (Carvalho et al., 2008; Castéra & Clément, 2014; Clément & Caravita, 2014; Clément, 2015) shows that teachers from diverse countries have vastly different views on these issues.

For instance, consider the responses to one statement about the possible biological justification of women's roles—"It is for biological reasons that women more often than men take care of housekeeping"—in a comparison study of more than eleven thousand teachers from 33 countries. Figure 1 includes data from biology teachers only in nations where teachers agreed or disagreed most with the statement. We see that approximately 70% of biology teachers in Algeria and Georgia generally agreed with the statement, whereas in Italy, Spain, Serbia, and France 3–10% of teachers agreed.

Similar differences in the opinions of biology teachers from different nations were also found in many other questions. For instance, in response to a statement about the environment, "Our planet has unlimited natural resources," more than 95% of teachers disagreed in Germany and Finland, whereas only 20% held that same view in Morocco and Lebanon (Clément & Caravita, 2014). With respect to the origin of life, more than 80% of teachers in Algeria and Morocco chose a creationist response, compared with just 1% in Estonia, France, and Sweden. Many teachers (e.g., 60% in Malta) who believe in God revealed their evolutionist and creationist views when they indicated that the processes of evolution are controlled by God (Clément, 2015). Other important examples of national differences can be found in Clément and Castéra (2013) and Castéra and Clément (2014). These findings show that there are differences of conception about these issues among those charged with teaching science content. This knowledge certainly implies a future domain of research related to the sociocultural influences on what is taught in each country. To extend this kind of analysis, future research might use two key concepts: KVP (knowledge, values, and practices) and DTD (didactic transposition delay), which I briefly present here.

Using KVP as a Foundation for Future Research in Biology Education

In considering the possible interactions KVP between scientific knowledge (K), values (V), and social practices (P) (Clément, 2006, 2013), we can start with an example such as the results of an analysis of the images of identical twins included in the biology textbooks of eighteen countries (Clément & Castéra, 2013). This revealed that in all cases, the twins had the same clothes and hairstyle. Science knowledge (K: "genotype → phenotype") is linked to implicit values (V: sociocultural features being determined by genes, innate ideas, fatalism) and to social practices (P: the way parents dress their children; the way publishers choose the images for their textbooks). This example illustrates interactions between the three poles K, V, and P.

More generally, any conceptions can be analyzed as possible interactions between these three poles of KVP (Figure 2). For instance,

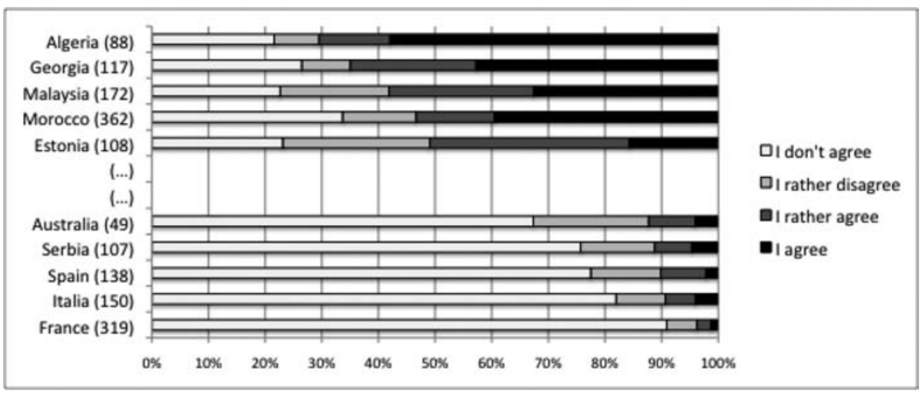

Figure 1. Section of a larger data set featuring the responses of 5,024 biology teachers, grouped by country in descending order of most agreement to most disagreement, to the statement, "It is for biological reasons that women more often than men take care of housekeeping."

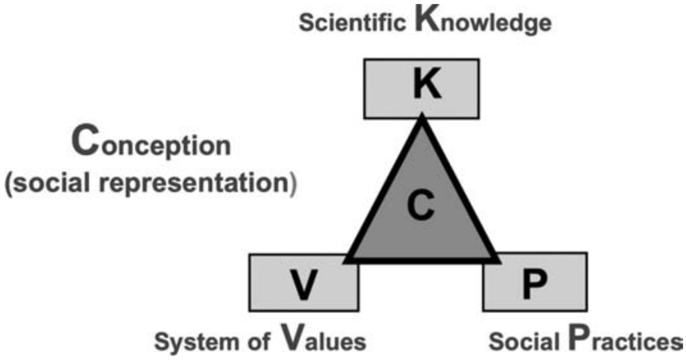

Figure 2. In the KVP model, any conception (C) can be analyzed as a possible interaction among the three poles of K (knowledge), V (values), and P (social practices) (Clément, 2006, 2013).

since the studies of Broca at the end of the nineteenth century, some assumed that women were less intelligent than men because of their smaller brain size. Here, knowledge (K = brain size) was interacting with sexist values (V) and social practices (P). Of course, there is no correlation between intelligence and size of brain (new K), and gender equality is a citizenship value promoting more equality in social practices. Even if there are gender differences, such biological differences cannot justify gender inequality in action.

Figure 2 illustrates another sexist KVP interaction: in several countries, many biology teachers can justify by (outdated) biological reasons (K) that women should do more housekeeping than men, knowledge linked with local social practices (P) that are rooted in more or less sexist values (V).

The conceptions of the different actors within the educational system can be analyzed as possible KVP interactions at all the levels of the didactic transposition: learners' conceptions, but also the conceptions of teachers; of authors of curricula, textbooks, and other documents; and even the conceptions of researchers who published the scientific references of the didactic transposition.

Considering Didactic Transposition Delay (DTD) in Biology Education Research

DTD is defined as a measure of the delay between the publication of a new scientific concept and its introduction in instruction (in syllabi, curricula, or textbooks) (Quessada & Clément, 2007). Not surprisingly, scientific knowledge is updated frequently, sometimes in substantial ways, but often what is taught changes only slowly, with delays differing from one country to another. Therefore, the measure and interpretation of DTD could be an important approach in studying the sociocultural and economic influence on the content of taught biology across nations.

For instance, the issue of human origins has not yet been included in the textbooks of some countries (such as Algeria) and was recently suppressed in others (such as Lebanon). Important new biological concepts such as epigenetics, cerebral epigenesis, and transposons are not yet introduced in the secondary school curricula of several countries. There is also the challenge that ideas that are taught may be partially outdated. For instance, in countries that still refer to the "genetic program" and not yet "genetic information" (Clément & Castéra, 2013), the choice of the word "program" may be ideological, suggesting that all our traits, competences, and performances are already written in our DNA. Consider an example of a biological fact: In the 1970s the number of human genes was estimated at 100 to 150,000, yet today this estimate is about 23,000. However, this new reality is not yet reflected in all biology textbooks. Thus, DTD can be an interesting indicator of sociocultural influences on what is taught in biology classes in each country.

With respect to the foundation discussed here, future research questions might involve

- The development of international comparisons of biology education, and historical approaches in various countries to identify the influences of different sociocultural and economical contexts (Once differences in the biology curriculum or way of teaching are seen between one country and another, it is important to try to understand how and why biology instruction differs in these cases.);
- The use of KVP to analyze the conceptions of the main actors of the educational system related to each topic of biology, health, or environment—conceptions of students and of teachers, as well as identifiable conceptions inside curricula, syllabi, textbooks, and other resources; and
- The use of DTD to analyze the speed of changes within syllabi, within textbooks, or even within teachers' conceptions and to suggest possible interpretations of the differences seen.

○ Empowering Students to Cope with Scientific Innovations: Lessons from Genomics Education

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Biological research has not only changed our views of life, disease, and behavior, but has also generated applications in many areas vital to humans, including food production, medical diagnosis and therapy, and forensics. The positive outcomes are many, but with these have come important dilemmas. Consider, for example, whether we should encourage or avoid using genetically modified organisms, or whether we should use medication for children with behavioral problems. Socioscientific issues such as these cannot be addressed solely through more biological research. Personal reflection and societal dialogue on these practices are needed to clarify the values and interests at stake and to explore possible scenarios and regulations.

One justification for biology education is to support citizenship, with the aim of empowering students for decision making by bringing both the findings of biology research and related implications into the classroom. Both the risks and benefits of recent technologies and findings should be addressed, but also the so-called "soft impacts" (Boerwinkel, Swierstra and Waarlo, 2014).

In 2002, the Dutch government started funding the Netherlands Genomics Initiative, channeling large funds for fundamental and applied genomics research while including humanities and social science research and societal dialogue activities. Our institute and the Cancer Genomics Centre collaborated in designing, implementing, and studying genomics education and communication. Our educational output consisted of mobile DNA labs (van Mil et al., 2010), teacher education workshops, teaching materials, and strategies for discussing ethical dilemmas. Our research, which we offer as a model in other science domains, consisted of addressing student problems in understanding the cellular and molecular mechanisms of disease, and focused on molecular mechanistic reasoning (van Mil et al., 2016), examining teachers' challenges when discussing ethical dilemmas in genetics (van der Zande et al., 2012), and finding international consensus on which genetic knowledge is required by scientifically literate citizens (Boerwinkel, Yarden and Waarlo, 2017).

Our involvement in research on cancer genomics informed our curriculum designs and suggested future work. We learned about how cancer genomics research reveals the ways in which cells are regulated, and how these new findings change our views on traditional and basic biological concepts such as gene, phenotype, and trait. Our meetings with genetic counselors showed how these professionals deal with statistics and what questions their patients and their families have, and the choices their clients must make. All these experiences were immensely fruitful in developing our thinking about biology education within a contextualized approach. The involvement of humanities scholars and social scientists made us aware of political aspects such as the regulation of diagnostic testing of embryos for the presence of BRCA gene variants (Robertson, 2003). Analyzing dilemmas such as those related to informing relatives about the possibility of carrying a high-risk gene variant taught us about the different conflicting moral principles.

Some recommendations for future research in biology education can be derived from this work. First, studying the personal and societal impacts of new scientific practices implies that we should analyze how the meanings of relevant biological concepts change (such as the concepts of "gene" and "trait"). Second, cooperation between biological researchers and with experts on related ethical, legal, and sociological issues is vital. Finally, the most generalizable conclusion we can offer is that this framework of involving a variety of experts and all stakeholders should be considered, no matter what biology content is the focus of instruction. No one method and no single group of experts would be enough.

In conclusion, we offer the following biology education research questions related to the work discussed here:

- How are biological concepts used contextually within innovative scientific and professional practices, and how do the meanings of these concepts in biology education differ from their traditional meanings?
- In what kinds of decisions should students be prepared to participate as citizens, and what do they need for informed decision making and acting?
- What are the consequences of adding concepts and skills to, or removing them from, the core biology curriculum?
- What are effective instructional strategies that stimulate reflection and argumentation in biology classrooms, and how can we prepare biology teachers to implement them?

○ Grand Challenges in Biology Education Research: Some Conclusions

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There was no expectation that our small group would provide all or even most of the recommendations that should be made about future directions in biology education research. However, the notion that those with expertise in biology education could suggest targeted research questions was intriguing. This work has influenced my thinking about research in biology education, so I will conclude with a few personal thoughts about potentially fruitful avenues for research. We could

- Examine potentially promising—but small—studies reported in the literature and encourage teams of researchers to engage in larger versions of those studies in wider contexts to permit inclusive and comprehensive conclusions.
- Engage in a series of meta-analyses of related research findings and/or produce reviews of the research literature linked to potentially useful areas of investigation.
- Consider the most effective organizational plan for biology instruction (e.g., should the study of cells come first, or would students respond better to a "big picture" environmental approach?).
- Add to recommended biological pedagogical content knowledge (B-PCK) by examining and reporting prior studies of students' alternative ideas and beliefs about biological phenomena, which can confound instruction.
- Include in B-PCK the determination and dissemination of useful analogies and examples.
- Examine how best to weave nature of science (NOS) ideas into the biology curriculum and teacher education programs.
- Most importantly, determine how to link the biology research community with practitioners and other stakeholders so that we can work to explore actual problems of interest and share research findings with those who can put recommendations into action.

No matter the specific perspectives each of us has offered, we share the goal that larger groups of researchers across wider educational and social contexts should be engaged to target future directions and potentially gain more conclusive answers to any questions of interest. We must have a more embracing conversation among a more diverse and multinational group of biology education researchers in cooperation with other stakeholders such as teachers, textbook authors, scientists, and policymakers. Only then can we identify and attack truly significant questions and propose ways in which our answers can inform biology education in meaningful ways. However, for now, we are pleased to offer these suggestions as small steps on the long road toward the determination of the Grand Challenges in Biology Education. Once these big questions are identified and their solutions considered in the widest settings and contexts possible, we will be positioned to enhance biology teaching and learning in the most effective and generalizable ways possible.

Note

1. Bayrhuber (2016) has explained that there is a distinction between didactics and teaching but Gericke and Ottander (2016) who have also explored that issue, have reached the conclusion that it is acceptable to see the two as similar enough to consider them synonyms. Therefore, it seems reasonable to use the terms "Research in the Didactics of Biology" and "Biology Education Research" interchangeably.

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