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Five Things Chemists (and Other Science Faculty) Should Know about the Education Research Literature

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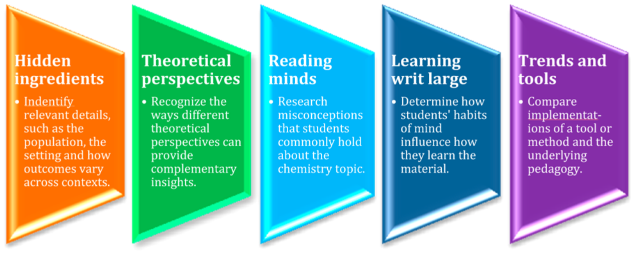
ABSTRACT: Faculty are increasingly expected to provide a more student-centered learning experience in their classes, including in large introductory courses. To do this, they may choose from a colorful palette of active learning approaches and tools that have been piloted in a wide variety of settings. Success, however, depends on more than the knowledge of what works and a commitment to implementing it. It requires a deep understanding of the principles of learning that underlie the approach or tool, which in turn requires fluency with the education research literature. While the literature is replete with implications for practice, much of it is written for education researchers rather than for science instructors. This brief commentary aims to help chemists and other faculty efficiently sift through this enormous body of work and glean insights about teaching and learning to improve their practice.



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■ INTRODUCTION

Although many empirical studies demonstrate the added value of active learning approaches (such as peer instruction and clickers) compared to traditional lectures, active learning instruction by science faculty members who lack a science education background commonly fails to improve learning.[1,2] Like an actor following a script without understanding how the historical and cultural context informed it, a science instructor implementing a curriculum or teaching approach without understanding the theory and research behind it may enact it in a way that only superficially resembles what its creators intended. Instructors need to understand both *what* works and *why* it works, "so that adaptations of a given method remain aligned with research about its effectiveness" (ref 3, p 10). Science instructors who want to reform their teaching can thus benefit greatly from going beyond the script. Wading into the education research literature, however, can quickly leave one adrift in a vast sea of lengthy papers that seem full of impenetrable jargon and insider disputes. This brief commentary highlighting five important aspects of education research presents a framework to help science instructors meaningfully draw on the literature to inform their teaching.

■ HIDDEN INGREDIENTS

Scientists learn to read papers in their fields with a critical eye, and how to efficiently locate relevant studies by skimming through numerous abstracts. Because education abstracts can be inadequately forthcoming about a paper's contents, skimming the paper itself may be necessary to distinguish a research study from a purely theoretical paper or a paper that describes an innovation but presents no learning data. Furthermore, atoms and molecules do not have bad days, and every atom of carbon-12 behaves like every other atom of carbon-12. In contrast, education findings may vary across contexts.

Yet even in the laboratory, replicating another's work can be tricky. In one case, chemists who spent months trying unsuccessfully to cleave benzylic carbon−carbon bonds according to a published method discovered that the reaction was photochemically induced, not thermally induced as originally thought, and that iron salts leaching from an old stir bar used in the original study had acted as a catalyst.[4] Hidden ingredients can also explain disparate results in education research. For example, classroom demonstrations only result in learning gains when the students must predict the outcome before seeing it.[5]

As in the sciences, review papers can be pure gold for education research neophytes and veterans alike, and meta-analyses (such as refs 2 and 26) are especially valuable. A meta-analysis not only reviews the findings from papers on a particular topic but also can provide a shortcut to finding relevant articles because it will include studies that use less common terminology to describe the same phenomenon, and it will exclude studies that fail to meet basic design standards. Meta-analyses also combine the effect sizes of the individual studies to provide a statistical measure of the strength of a phenomenon, such as how much active instruction benefits learning. The range of effect sizes, and the existence of both positive and negative effect sizes, can reveal hidden ingredients that make some interventions work while others fail—

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ingredients key to helping instructors successfully implement a curriculum innovation in their setting.

THEORETICAL PERSPECTIVES

Disagreements and debates, a natural part of the process of science, are even more prevalent in the education research literature. One important reason for this is that education research draws on the knowledge and methods of several disciplines, including cognitive science, neuroscience, psychology, sociology, and philosophy. The range of world views represented across these disciplines leads to clashes within education. Education research papers are often surprisingly lengthy compared to science papers because education researchers must not only present the technical details of their methods but also give the rationale for choosing one research paradigm over another.

Yet, just as chemists learn from both inductive and deductive approaches to a scientific problem without getting bogged down in philosophical discussions about the nature of science, chemistry instructors can learn from work driven by different theoretical perspectives without entering the fray. In terms of informing classroom practice, these theoretical perspectives can be complementary, rather than competing.[6] For example, active learning is consistent with constructivism—the view that individuals must construct their own understanding—which is informed by both a cognitive perspective on learning and a sociocultural perspective.

In the cognitive perspective, the research focus is on the learner's understanding and mental representations. In the sociocultural perspective, the research focus is the role of the milieu of social interactions and culture in which the learner is embedded. In implementing a new instructional approach, instructors benefit from knowing how individual learners' knowledge of a topic transforms, as well as how the classroom norms, discourse, and practices set the stage for, or hinder, learning.

READING STUDENTS' MINDS

The education research literature contains a Pandora's box of the ideas that learners of all ages have about science. For example, even students who have taken introductory chemistry may believe that molecules change size in different phases, and they may draw diagrams of molecules growing from small to large spheres when heated.[7] It is tempting to view students' misconceptions as weeds to be rooted out to allow the relevant scientific ideas to be planted in their place. This approach is likely to fail, however, because (i) students' ideas are highly complex; (ii) they shape how students attend to new information; (iii) small changes in the way a question is posed can evoke different responses from a student; and (iv) new misconceptions regularly arise during instruction.[8,9]

Consider, for example, a common misconception that students have about the mechanism of the greenhouse effect (Figure 1). Many students provide a chimera explanation of the greenhouse effect that fuses two distinct environmental issues, global warming and depletion of the ozone layer. They state that the temperature of the earth increases because the hole in the ozone layer permits deeper penetration of sunlight.[10] Some students suggest that greenhouse gases like carbon dioxide break down the ozone layer.[11]

The ozone layer/greenhouse effect chimera explanation has its own internal logic, and it is easy to see why students could conflate two issues that both involve gases, earth's atmosphere, and solar radiation. Indeed, scientific links exist between these two issues. Some chlorofluorocarbons that damage the ozone layer are also potent greenhouse gases.[12] Ozone itself is a greenhouse gas.[13] Furthermore, increasing greenhouse gas concentrations lead to stratospheric temperature and wind changes that increase ozone depletion.[14] In other words, students' explanations of the greenhouse effect reveal knowledge that can serve as a foundation on which to build, rather than something to be rooted out. The literature contains many debates about the size and structure of students' ideas, and the implications for designing curriculum and assessments to bring students to a more scientific understanding.[15−18] Misconceptions research can help faculty develop instructional approaches that elucidate and address students' ideas. Concept inventories can be a good place to begin digging into one's own students' understanding.[19]

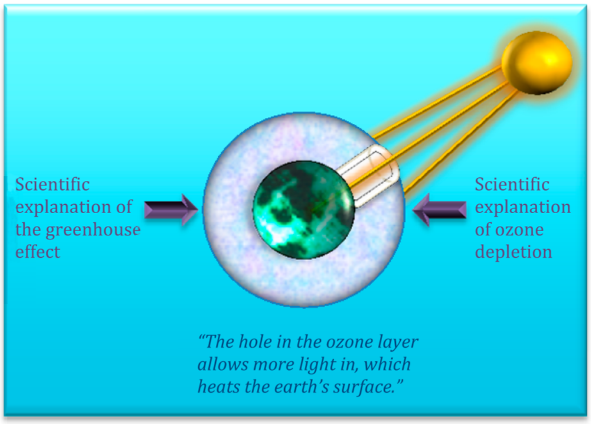

Figure 1. Students' chimera explanation of global warming.

LEARNING WRIT LARGE

Lines of research delve into different kinds of understanding and habits of mind relevant to science learning. In addition to conceptual knowledge, this includes students' ideas about the nature of science, metacognition, epistemology, and beliefs and attitudes. In science classes the focus tends to be on improving students' knowledge of science content and, through laboratory experiences, their knowledge of the nature or processes of science. Allocating more attention to metacognition, epistemology, and beliefs and attitudes can advance instructors' curricular goals.

Metacognition is the awareness of and ability to reflect on and regulate one's own thinking.[20] It plays an important role in students' general study habits as well as domain-specific problem solving. Research has shown that as little as 1 h of explicit instruction on metacognitive learning strategies, such as self-questioning, can significantly improve students' performance in general chemistry.[21] Cooperative problem-based laboratory instruction, without explicit instruction on metacognition, improves students' ability to regulate their own thinking and their problem-solving ability.[22]

Epistemology refers to an individual's views about how knowledge is defined and justified and what counts as a sound explanation in a discipline.[23] Courses that encourage rote memorization and fail to connect the material to students' prior knowledge implicitly present an inappropriate epistemology, while reformed classes that focus on coherence, mechanisms, and questioning assumptions help students develop an epistemology that better reflects the discipline.[24]

Studies of beliefs about learning, intelligence, and motivation have shown that even brief activities that encourage students to adopt a growth mindset toward their ability in a subject area can have large payoffs in terms of learning in the course, especially for students from underrepresented groups.[25] Thus, research on metacognition, epistemology, and beliefs can help science instructors improve not only students' habits of mind but also science learning outcomes.

■ TRENDS AND TOOLS

Today's education trends are mainly technology-based. A meta-analysis of the experimental studies published between 1990 and 2010 on computer-based technology in postsecondary education (1105 papers selected from an initial pool of 11,957 study abstracts) found an overall modest positive impact on students' attitudes and learning.[26] The critical factor that emerged was *not how much* technology was used (in fact low to moderate usage of technology was more favorable than high usage) *but how* technology was used. Some ways of implementing technology resulted in much larger positive impacts, and others were detrimental to learning (i.e., negative effect sizes). In general, pedagogical uses of technologies that merely enhanced presentation of information (e.g., PowerPoint, visualizations) had smaller effect sizes than those that provided cognitive support for learners (e.g., feedback, simulations, wikis), but variability existed within these categories. For example, in one study, cognitive supports in the form of computer-generated prompts had a strong negative effect on learning because students receiving the prompts unexpectedly made less use of online discussion boards than students who did not receive the prompts.[27]

These findings show that the effectiveness of the latest educational innovations depends on how they are implemented and the pedagogy behind them. It follows that using "old innovations" can be a perfectly valid way to reach one's instructional goals. Concept maps, for example, are not rendered passé as an education tool just because they became fashionable in the era of leg warmers.[28] Cases in which any educational innovation works in one context and fails in another reveal the importance of treating innovations not as black boxes with prescribed inputs and expected outputs but as processes with the potential to provide insights into learning. Such insights can, in turn, be used to improve instruction.

■ CONCLUSIONS

All educational innovations undergo mutations when put into practice; the challenge is determining how to avoid lethal mutations.[29] In an effort to achieve fidelity of implementation, instructors new to active learning instruction may focus on the surface features of the task, believing that, for the activity to work, first and foremost the choreography must be in place. Ironically, this emphasis on the "active" in active learning may cause an instructor to lose sight of the learning. Students may go through the motions without thinking deeply about the science. To avoid such lethal mutations, instructors need to understand the key underlying principles that link the components of an activity to learning, because, as this discussion of five things science faculty should know about the education research literature highlights, teaching and learning are inextricably linked. With this understanding, faculty are primed to enter mutually beneficial collaborations with colleagues who are chemistry education specialists.[30] Advancing such relationships can create a culture of scholarly teaching within departments, in which faculty informed by the literature consistently use student learning outcomes to iteratively refine their instruction.

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Notes

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