

Where's the evidence that active learning works?

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Michael, Joel. Where's the evidence that active learning works? *Adv Physiol Educ* 30: 159–167, 2006; doi:10.1152/advan.00053.2006.—Calls for reforms in the ways we teach science at all levels, and in all disciplines, are wide spread. The effectiveness of the changes being called for, employment of student-centered, active learning pedagogy, is now well supported by evidence. The relevant data have come from a number of different disciplines that include the learning sciences, cognitive psychology, and educational psychology. There is a growing body of research within specific scientific teaching communities that supports and validates the new approaches to teaching that have been adopted. These data are reviewed, and their applicability to physiology education is discussed. Some of the inherent limitations of research about teaching and learning are also discussed.

learning; teaching; science education; physiology education

THE PUBLICATION of “*A Nation at Risk: the Imperative for Reform*” by the National Commission on Excellence in Education in 1983 (75) was only the first of many recent calls for the reform of K–12 science education in the United States. The following year, the Association of American Medical Colleges (4) called for significant changes in the teaching of basic sciences to medical students. In 1990, the National Research Council (76) identified problems with biology education in our nation's high schools, and, more recently in 2003 (77), it voiced concerns about the way in which undergraduate education in biology is carried out. All of these critiques have urged us to adopt approaches to teaching that more actively involve the student in the learning process, that focus on problem solving as well as memorization, and that lead to more long-lasting, meaningful learning (see Refs. 61 and 70 for discussions of educational reforms in the life sciences).

One of the most pointed critiques of the state of science education was articulated by Volpe in 1984 (107), and his words are as relevant today as they were more than 20 years ago.

Public understanding of science is appalling. The major contributor to society's stunning ignorance of science has been our educational system. The inability of students to appreciate the scope, meaning, and limitations of science reflects our conventional lecture-oriented curriculum with its emphasis on passive learning. The student's traditional role is that of a passive note-taker and regurgitator of factual information. What is urgently needed is an educational program in which students become interested in actively knowing, rather than passively believing.

More recently, Halpern and Hakel (32) observed that “. . . it would be difficult to design an educational model that is more at odds with current research on human cognition than the one

that is used in most colleges and universities.” Apparently, not much has changed since 1984.

It would seem that we need to do something to change the way that science is taught, and we need to do it now.

At the same time that reforms are being proposed, there is a growing call to base educational decision making on evidence from high-quality educational research (“evidence-based education”). At the K–12 level, this is now a matter of national legislation. The No Child Left Behind (NCLB) Act of 2001 (Ref. 38a; see www.ed.gov/policy/elsec/leg/esea02/index.html if you want to read all 670 pages of this legislation) mandates that federally funded programs be based on rigorous scientific research, and the Education Sciences Reform Act of 2002 (38) essentially describes what constitutes rigorous research paradigms in education. Eisenhart and Towne (23) have published a very useful discussion of the implications these two pieces of legislation.

In the sphere of medical education, Van der Vleuten, Dolmans and Sherpber (106), and Murray (74) have pointed out the need for a research base for reform in medical education. Norman (81) has raised some cautions about the problems of doing this research but clearly supports the need for such data. The National Research Council report of *Scientific Research in Education* (78) is an in-depth discussion of how meaningful data about teaching and learning should be obtained.

As scientists, we have been trained to make decisions based on evidence, and it is appropriate to ask where the evidence is that these proposed new approaches to teaching and learning, these reforms, work any better than the old approaches from which we all learned and from which our students seem to be learning. The short answer is that there IS evidence out there and that it does support the claims made by advocates of reform. The purpose of this article is to present some of that evidence and discuss its applicability to physiology teaching. I will first present some of the relevant evidence from the sciences basic to education (cognitive psychology, educational psychology, and the learning sciences) and then present some of the evidence that comes from some science disciplines. I will also try to provide a road map to help in finding the relevant literature and some guidelines in reading it critically.

Like any of the scientific fields with which we are most familiar, educational research is generating an ever-growing data base, and it is becoming increasingly difficult to keep up with the literature. **It is not feasible to review every topic relevant to physiology teaching and learning, and the exclusion of any topics (authentic assessment, the uses of computers, or the importance of animal use in the student laboratory) does not mean that they are unimportant. Not everything could be included here.**

The references cited here are a necessarily idiosyncratic selection, with one of the selection criteria being the accessibility of the sources cited (for example, no conference pro-

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ceedings, which in the fields discussed here are very common, have been included). I have also tried to identify monographs and review articles that are particularly relevant, but I have also included some of the original articles reporting important results. Unlike fields such as molecular biology or physiologic genomics, “old” findings in educational research continue to be germane today, and the work cited here spans the last 40 years of research.

What Is Active Learning and What Are These New Approaches to Learning?

What are the specific reforms or “innovative” approaches to teaching that “. . . more actively involve the student in the learning process?” Table 1 contains a partial list of such approaches to learning taken from Michael and Modell (61); each is discussed (to varying extents) in the discussion that follows.

The approaches to teaching listed in Table 1 are commonly said to involve “active learning” and to be “student centered.” These terms have been succinctly defined as follows (18):

Active Learning. The process of having students engage in some activity that forces them to reflect upon ideas and how they are using those ideas. Requiring students to regularly assess their own degree of understanding and skill at handling concepts or problems in a particular discipline. The attainment of knowledge by participating or contributing. The process of keeping students mentally, and often physically, active in their learning through activities that involve them in gathering information, thinking, and problem solving.

Student-Centered Instruction. Student-centered instruction [SCI] is an instructional approach in which students influence the content, activities, materials, and pace of learning. This learning model places the student (learner) in the center of the learning process. The instructor provides students with opportunities to learn independently and from one another and coaches them in the skills they need to do so effectively. The SCI approach includes such techniques as substituting active learning experiences for lectures, assigning open-ended problems and problems requiring critical or creative thinking that cannot be solved by following text examples, involving students in simulations and role plays, and using self-paced and/or cooperative (team-based) learning. Properly implemented SCI can lead to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes towards the subject being taught.

Pedersen and Liu (85) point out that “student centered” is usually defined in opposition to “teacher centered,” and Barr and Tagg (6) have discussed a change in the educational paradigm from one that focuses on teaching to one that focuses on learning. For example, a conventional lecture-based course is said to be teacher centered because of the view that what

matters most in determining what is learned is what the teacher does in the lecture hall. It is, of course, understood that what the students do in response to the teacher’s lectures matters, but the focus is on the teacher in the front of the classroom. A student-centered learning environment is one in which the attention is on what the students are doing, and it is the students’ behavior that is the significant determinant of what is learned. Again, it is acknowledged that what the teacher does matters greatly (after all, it is the teacher who designs and implements the learning environment), but the attention here is firmly on the students.

Alexander and Murphy (1) have discussed the research behind learner-centered approaches, and Walczyk and Ramsey (108) have described the application this approach in college science classrooms.

What is it that the students should be doing in a typical student-centered active learning environment? Michael and Modell (61) have described the process as building mental models of whatever is being learned, consciously and deliberately testing those models to determine whether they work, and then repairing those models that appear to be faulty. This description seems consonant with the definition of active learning previously presented. Students learning in this way are more likely to be achieving meaningful learning (5, 59, 60, 68, 82).

Evidence From the Learning Sciences, Cognitive Science, and Educational Psychology Supporting Active Learning

How do we know that student-centered, active learning approaches work and that they work better than conventional, teacher-centered, usually passive approaches?

There have been several attempts to collate and summarize research findings from psychology and other fields that relate to teaching and learning. Lambert and McCombs in 1998 (44) and Bransford et al. in 1999 (11) have both published important books in which these findings are summarized. The Bransford et al. book, in particular, has been very influential in shaping the thinking of the education community. These works, and there are many others, deal with learning across all the disciplines. Michael and Modell (61) have reviewed our current understanding of the learning process and discussed key ideas about learning that apply to active learning in the science classroom.

The following are brief descriptions of some of the key findings that need to be incorporated in our thinking as we make decisions about teaching physiology at any educational level. These ideas are accepted by essentially all researchers (11, 44), although the comments here are somewhat simplified. No attempt has been made to describe all of the controversies that remain unresolved. I have underlined some of the key terms that occur in this literature because their use is essential in doing electronic searches for additional information.

1. *Learning involves the active construction of meaning by the learner.* This is the fundamental tenet of “constructivism,” the dominant paradigm in psychology and the learning sciences. As Driver et al. (22) state, “The view that knowledge cannot be transmitted but must be constructed by the mental activity of learners underpins contemporary perspectives on science education.” Learners construct meaning from the old information and models that they have (the foundation, if you

Table 1. *Some student-centered, active learning approaches from Michael and Modell (61)*

Problem-based or case-based learning
Cooperative/collaborative learning/group work of all kinds
Think-pair-share or peer instruction
Conceptual change strategies
Inquiry-based learning
Discovery learning
Technology-enhanced learning

will) and the new information they acquire, and they do so by linking the new information to that which they already know. The construction of meaning is facilitated by making multiple links between the information being acquired and the existing store of information. Information and meaning (whether old or new) are assembled into mental models or representations. One technique that is known to help students build useful mental models is concept mapping (83). Building multiple models or representation facilitates meaningful learning (68) or learning with understanding (98).

It follows, then, that to the extent that old knowledge and old models are faulty, meaningful learning will be compromised. These faulty or flawed mental models are referred to by a variety of terms, with the terms “misconceptions” or “alternative conceptions” perhaps carrying the fewest specific implications. The review by Wandersee et al. (27) is a good starting point for understanding this phenomenon. Modell et al. (71) have discussed some of the problems with the terminology that is used in this field and also presented some of the reasons for attempting to diagnose the presence of misconceptions in one’s students. Learning can be thought about as a process of conceptual change in which faulty or incomplete models are repaired (46, 99, 110). “Fixing” faulty mental models, or misconceptions, is universally recognized as being extremely difficult to accomplish, although there are an increasing array of techniques that have been shown to help. Smith et al. (100) and Chi (14) have presented some interesting and potentially useful thoughts about misconceptions and their remediation.

2. *Learning facts (“what”—declarative knowledge) and learning to do something (“how”—procedural knowledge) are two different processes.* Ryle (94) was perhaps the first to point out the difference between “knowing that” something is true and “knowing how” to do something. In psychology (2), this has come to be referred to as the difference between declarative knowledge (“knowing that”) and procedural knowledge (“knowing how”). It is increasingly clear that the challenge of learning the facts about a physiological mechanism is quite different than the challenge of learning to solve problems with those facts. So, if you expect students to use knowledge to solve any kind of problem, you must provide them with opportunities to practice the needed skills and receive feedback about their performance. Romiszowski (92) has reviewed what is now known about learning a physical (psychomotor) skill and has stated the principles that apply to this learning task. Table 2 contains some of Romiszowski’s “rules” for promoting skills learning and describes their application to learning problem-solving skills. Segal and Chipman (96) have assembled an interesting collection of articles on teaching problem-solving skills.

3. *Some things that are learned are specific to the domain or context (subject matter or course) in which they were learned, whereas other things are more readily transferred to other domains.* Transfer (86) is said to occur when learning of one subject or topic (or in one context) affects learning in another subject or topic (or in a different context). It is important to note that transfer can be either positive or negative, although most discussions of transfer focus solely on positive transfer because this is obviously the desired outcome of learning.

All aspects of transfer continue to be quite controversial (33, 56): What does it mean, How does one determine whether it

Table 2. *Some “rules” for promoting skills learning [from Romiszowski (92)] and their application to learning problem solving*

“Let the student observe a sequential action pattern before attempting to execute it.”
“Demonstrate a task from the viewpoint of the performer.” <i>Model the problem-solving process for students (57, 58).</i>
“Setting a specific goal can lead to more rapid mastery of a skilled activity.” <i>Ensure that students understand what it means to solve different kinds of problems (58).</i>
“In general, ‘learning feedback’ (results information) promotes learning, and ‘action feedback’ (control information) does not.” <i>Letting students complete the problem-solving task before getting feedback about their success promotes learning better than providing feedback at each step in the solution (23).</i>
“In general, feedback is more effective in promoting learning when it transmits more complete information.” <i>Students learning to solve problems need more than just an assessment of whether their answer was correct or not (58).</i>
“Transfer and retention of motor skills are improved by ‘overlearning.’” <i>The more problems students solve (with appropriate feedback), the more readily they will be able to solve novel problems, a defining characteristic of meaningful learning (55).</i>
“Avoid too fast a progression to more difficult tasks.” <i>Present the student with a sequence of problems that moves from easy to hard as their performance improves (23).</i>

has occurred, What conditions promote it, and What conditions hinder its occurrence? However, the issue is so central to all discussions of learning that it is essential that it be considered.

For example, in teaching physiology, there are at least two different issues in which transfer, or failure to transfer, is of great significance. Physiology is a science that is based on physics and chemistry. To understand many important physiological phenomena requires that students be able to apply an understanding of physics (the electrical properties of membrane or the mechanical properties of the lungs and chest wall) or chemistry (action of hormones, digestion, and acid/base balance). However, it is certainly NOT uncommon to observe that regardless of students’ prior physics and chemistry courses, they are unable to apply what they know in learning physiology (42); transfer often fails to occur. There is another way in which the occurrence or failure of transfer is relevant in physiology education. When students learn the relationships among pressure, flow, and resistance in the circulation (hemodynamics), it is reasonable to expect some transfer so that their understanding of airflow in the respiratory tree comes more easily or more quickly. However, here too it is common to observe that there may be little or no evidence of transfer. Modell (69) has advocated the explicit development of what he calls general models or common themes to promote this kind of transfer.

4. *Individuals are likely to learn more when they learn with others than when they learn alone.* There are now a great many different approaches to facilitating students learning together (as opposed to learning individually). Labels such as cooperative learning, collaborative learning, peer learning, or problem-based learning each describe a different approach to getting students to learn together. Bossert (10), Lunetta (29), and Blumenfeld et al. (9) have provided useful overviews of some, but not all, of these approaches, their theoretical bases, and the research that supports them. Johnson et al. (39) have published

a meta-analysis of 164 studies of cooperative learning methods; they conclude that there is solid evidence in these studies to support the benefits of cooperative learning.

In the disciplines, there are impressive results that support the power of getting students to work together to learn. In the field of computer-aided instruction, there is a wealth of data showing that two or more students working together at the computer learn more than students working alone (40, 93). In physics, students generate better solutions to problems when they work cooperative than when they work alone (34), and peer instruction, developed by Mazur (51), has been shown to increase student mastery of conceptual reasoning and quantitative problem solving (20). In chemistry, students in cooperative learning groups show increased retention and higher scores on assessments than students learning the same material in conventional ways (21).

Michael and Modell (61) have argued that the similarities that these approaches share are more important than their differences. While there can be little doubt that students working together learn more, the key issue now is how to implement small group work to achieve maximum learning (17).

It is worth noting that there are many factors in a cooperative learning environment, whatever its specific format, that are thought to contribute to the success achieved. One of these is clearly the requirement that participants talk to one another, articulating their understanding of the subject matter, and asking and answering questions. As will be discussed below, these behaviors are now known to facilitate learning in all disciplines.

5. *Meaningful learning is facilitated by articulating explanations, whether to one's self, peers, or teachers.* It is a common belief that a central part of learning any discipline is learning the language of that discipline (Ref. 45 has an extended discussion of this idea, and Ref. 25 discusses a variety of language-related issues in tutoring students to solve cardiovascular problems). Learning a language requires practice using that language, and it is thus important that students have the opportunity to both hear (and read) and speak (or write) the language of the discipline being learned. Evens and Michael (25) have discussed the importance of language in learning cardiovascular physiology, whether from a human or a computer tutor. However, there is a more specific benefit of encouraging students to explicitly articulate their understanding of a topic. A large body of research, much of it by Chi (15, 16), has demonstrated that articulating self-explanations and using self-explanation improves learning. Rivard and Straw (91) have demonstrated that both talking about and writing about ecological concepts improves meaningful learning and retention.

The five "big" ideas described here represent the "basic science" foundation for teaching and learning that should form the basis for what we do to help our students learn, whether in our classrooms or outside of them. In the next section, I will review some of the applications of these ideas (and the results of some research) in four science disciplines: physics, chemistry, biology, and physiology.

Evidence About Active Learning From Education in the Sciences

Over the last 30 years, there has been a rising tide of research carried out within the science disciplines aimed at

understanding and promoting the teaching and learning in the disciplines. This research ranges from "laboratory" experiments (in which student learning outcomes are studied outside of the classroom and in a context divorced from a specific course) to classroom experiments (in which learning outcomes in a specific course/classroom are measured) to curricular experiments (in which approaches to learning than span a whole curriculum are compared). The "basic" research in the previous section represents a starting point for all of these studies. However, there is also a very rapidly growing body of work that addresses the specific problems and issues related to teaching and learning science. Some relevant books that review different aspects of this field are by Gabel (27), Gardner et al. (29), Glynn et al. (30), Minstrell and van Zee (65), and Mintzes et al. (68).

It is not possible to summarize all of this literature. Rather, I have attempted to describe some important themes underlying research on teaching and learning in four different fields and have cited some of the more interesting examples of work in these areas.

Physics. There is a long history of educational research being done by the physics education community, and a long history of attempts to reform the teaching of physics. Some of the first, and still most striking, demonstrations of misconceptions were uncovered in the domain of Newtonian motion (Ref. 52 discusses this early work).

This work on physics misconceptions led in a fairly direct way to the development of the force concept inventory (FCI) by Hestenes (35, 36), an assessment tool that focuses on students' understanding of the concepts of physics rather than the ability to analyze problems and solve them using equations. There are now a number of similar inventories in other areas of physics.

The availability of an assessment tool like the FCI has provided a valuable tool for the classroom teacher (95), but it has also provided a valuable tool for the educational research community. Although there are controversies about the FCI, it has provided a measure of student conceptual learning that can be used in asking questions about the efficacy of different approaches to teaching physics. One of the most striking findings (31) came from a comparison of the learning outcomes (as measured by the FCI and a related inventory on mechanics) from 14 traditional courses (2,084 students) and 48 courses using "interactive-engagement" (active learning) techniques (4,458 students). The results on the FCI assessment showed that students in the interactive-engagement courses outperformed students in the traditional courses by 2 SDs. Similarly, students in the interactive-engagement courses outperformed students in the traditional courses on the mechanics assessment, a measure of problem-solving ability. This certainly looks like evidence that active learning works!

Research in physics education is having a profound effect on the development of instructional materials. Research to determine what students know and can do and what they don't know or can't do in the domain of electricity by McDermott's group (53) has thus led to the development of instructional materials by this same group that do a better job of helping students master this subject matter (97). A similar approach has been pursued in the domain of optics (112). The interactive-engagement physics courses studied by Hake (31) used instructional

approaches based on research findings from within the physics education community.

Chemistry. Educational research in chemistry has focused quite strongly on uncovering the misconceptions that students at all educational levels (K–graduate school) bring to the chemistry classroom. One of the best reviews, or catalogs, of these misconceptions has been assembled by Kind (41). As the understanding of the prevalence and robustness of these misconceptions has been clarified, much attention has been turned to the efficacy of various teaching techniques to help students repair their faulty mental models. Towns and Grant (105) have studied the effects of cooperative learning and reported that students believe that it significantly contributed to a greater understanding of the concepts of physical chemistry. Niaz et al. (79) demonstrated that greater conceptual understanding resulted from using a teaching approach that included student generated arguments/counterarguments than from conventional approaches. Quílez-Pardo and Solaz-Portolés (88) have shown that the teacher’s own misconceptions about equilibrium contributes to the misconceptions that students have about this same phenomenon.

Chemistry, like physics, is a discipline in which the ability to solve problems is regarded as an essential part of mastering the discipline. Studies of problem solving in chemistry by experts and novices (students) have a long history, and Gabel and Bunce (27) have provided a comprehensive review of some of the early work on this topic.

Finally, a great deal of thought has gone into a variety of issue about the chemistry curriculum . . . what ought to be taught, to whom, when, and how. The pages of the *Journal of Chemistry Education* are filled with articles discussing the many issues that arise. In almost all cases, the discussion of these issues is grounded in the growing understanding of the problems that students have in learning chemistry.

Biology. Biology is a very large discipline, as a look at any recent biology textbook will attest. It is also a highly integrative science in three quite different ways. First, biology builds on and depends on other disciplines such as physics and chemistry. Second, the subject areas encompassed by biology relate to one another in a way that is different than the way in which the subareas of physics relate to each other; physiology and histology clearly overlap and integrate ideas from each other in a way that electricity/magnetism and mechanics do not. Finally, understanding biology requires students to be able to deal with phenomena at multiple levels at the same time: molecules to cells to organs to whole organisms.

The result is that any discussion of teaching and learning biology must recognize that students’ understanding (or misconceptions) about physics, chemistry, and other topics in biology will impact student learning about the particular biology topic of interest. It also means that active learning techniques must target physics and chemistry misconceptions as well as biology misconceptions. Michael et al. (63) have shown that at least some student misconceptions about cardiovascular phenomena are the result of the inability to apply certain general physical models (pressure/flow/resistance, for example) to physiological phenomena.

There is a long history of studies of children’s understanding of biological concepts that goes back to Piaget. One particularly fruitful topic of investigation has been children’s understanding of the cardiovascular system (3, 67) and how their

views evolve into the misconceptions that are present when students enter our classrooms. There have also been a number of studies of student misconceptions about photosynthesis (29, 47, 67).

The use of a variety of pedagogical treatments to help students repair misconceptions and to develop more appropriate concepts (a process referred to as conceptual change; see Refs. 46 and 99) have been explored by biology teachers and researchers. Concept mapping, written about extensively by Novak (83), is one technique that has been extensively explored, perhaps because the nature of biological knowledge lends itself to the hierarchical organization of ideas. Briscoe and LaMaster (12) have described one attempt to help students achieve meaningful learning with concept mapping and reported some significant success. Eisobu and Soyibo (24) have described a more complex study with more quantitative measures; they found significant learning gains with concept mapping. A volume by Fisher et al. (26) has described the uses of concept mapping in biology to achieve a number of educational goals.

Two other instructional techniques that are said to encourage active learning have also been explored. Discovery-based or inquiry-based learning is a powerful pedagogical approach that has much evidence supporting its use. These approaches are characterized as exhibiting (49) the following:

- (a) a focus on ideas and concepts, rather than on conceptually unrelated pieces of information;
- (b) a strong activity-participation component where students [are] motivated to “learn by doing;”
- (c) an emphasis on learning the methods of verifying and testing hypotheses in each field; and
- (d) the idea that content and process are inseparable components of learning.

The volume edited by McNeal and D’Avanzo (55) contains many examples of the application of these ideas in what they refer to as “student-active” science. Svinicki (103) has provided a brief overview of discovery learning for the physiology community.

Support for discovery learning is provided by a study in which students engaged in a course that incorporated some discovery learning exercises were tested, and their performance on questions related to topics learned through discovery learning was compared with their performance on questions related to topics learned in lecture (111). The authors concluded that performance was better on those topics learned through discovery learning.

Peer collaboration is another technique that has a sound theoretical basis, and students learning about photosynthesis in collaborative groups were found to have performed better than students learning alone (47).

One final report is worth noting. Burrowes (13) compared learning outcomes in two sections of the same course taught by the same teacher. One section was taught in the traditional teacher-centered manner (control group of 100 students), whereas the other section was taught in a manner that was based on constructivist ideas (experimental group of 104 students). The results of this experiment were striking: the mean exam scores of the experimental group were significantly higher than those of the control group, and students in the experimental group did better on questions that specifically tested their ability to “think like a scientist.”

We can certainly conclude that active learning, however the teacher “engineers” that experience for his or her students, works.

Physiology. Readers of this journal do not need to be told that the physiology education community has begun to make significant contributions to research on teaching and learning. With apologies in advance to those colleagues whose papers I do not cite, here is a sampling of the kinds of issues related to teaching and learning physiology that are currently being explored and have been published in *Advances in Physiology Education*.

The exploration of misconceptions about physiology held by students has begun, and the findings are similar to those in other fields of study (37, 58, 90). Given that you know that students in your class are likely to have a misconception, what can you do to help them repair their faulty mental model? Studies of the use of laboratory experiences to repair misconceptions have been carried out by Modell et al. (72, 73) and suggest easily implemented teaching paradigms that might help. A sophisticated concept mapping procedure for exploring students understanding of pulmonary physiology has been reported (54) and shows promise of providing a novel and useful assessment tool for conceptual understanding. Peer tutoring is a teaching technique that has had much support in the educational research literature, and Lake (43) has shown that it helps students learn physiology. Problem-based learning (7) is an approach to learning that has been adopted by many medical schools around the world. Mierson (64) has described an undergraduate physiology course taught in a problem-based learning mode, and Correa et al. (19) have described an interesting application of problem-based learning in a pathophysiology course. Finally, one last example of a topic that is being vigorously researched is computer-based approaches to reaching and learning, and Rawson and Quinlan (89) have reported on the outcomes of using such a program in the domain of acid-base balance.

For some reason, cognitive scientists and learning scientists have done relatively little work with issues of teaching and learning in physiology, but there have been some interesting studies. Spiro and associates (107) have looked at complex misconceptions and the use of analogies to help students correct them. Their results offer a cautionary note to the common use of analogies in teaching science: oversimplified analogies can be a source of student misconceptions. Odom and Barrow (84) have studied students’ conceptual understanding of diffusion and osmosis and have developed an assessment tool for this knowledge domain. Finally, there has been interesting work about students’ teleological thinking and what exactly it means (104, 113); in some cases, the problem arises out lack of fluency in the language of physiology, not in a faulty mental model. This is certainly an issue that has particular resonance with physiology teachers.

So, while teaching and learning issues in physiology have only recently begun to be explored, progress is being made, and the physiology teaching community itself is at the forefront.

An Important Caveat: Active Learning Doesn’t Just Happen

Active learning, student-centered pedagogical approaches put the focus on the learner and what the learner does. How-

ever, active learning doesn’t just happen; it occurs in the classroom when the teacher creates a learning environment that makes it more likely to occur (see Refs. 55, 61, and 70 for ideas that can be used in your classroom). Implementing these newer approaches to teaching requires the teacher to become a learner, because if these approaches aren’t implemented in a well thought out way, their outcomes will certainly not meet expectations.

Thus, one of the critical issues is faculty development, helping teachers to become familiar with new approaches to teaching and helping them gain experience actually implementing them. There are many avenues for such faculty development and much discussion in the literature about these issues, but this is not the place to pursue this topic.

Problems of Doing Research on Teaching and Learning

Active learning works. It should be clear that there are large bodies of evidence from a number of different fields supporting the effectiveness of active learning, although only a sampling of the results could be presented here. However, there are two additional issues that must be addressed. How applicable is the evidence and how sound is it?

Much research on school learning of science has been done with K–12 students as subjects. There is a growing body of research with undergraduates, and a more limited amount of research has been done with medical and other professional students. However, many, but admittedly not all, of the issues about learning and teaching science are common to all educational levels. **So, results from experiments or studies with middle school children learning science ARE relevant to understanding how medical students learn physiology (and vis a versa).**

It is also important to recognize that while learning physiology has many important similarities with learning physics (or anatomy), there are also important differences that are the consequence of the significant differences between the various science disciplines.

Thus, it would be unreasonable to expect that the results from educational research involving students very different from your students learning a discipline different than your discipline will translate into a recipe for how you should teach in your classroom. But, the mass of accumulating evidence for all grade levels and disciplines certainly should be used to guide your decision making about how to best help your students learn your discipline.

That said, it is important to recognize that educational research is difficult to do; this has been cogently highlighted by Berliner (8) in “Educational research: the hardest science of them all.” Berliner points out that unlike a physics experiment, in which it is possible to readily distinguish between the independent and dependent variables, and also possible to isolate and control all of the independent variables, in educational experiments all of this is problematic. Researchers may not agree on which variable is the dependent variable of greatest interest or importance. There may be disagreements about which independent variable(s) are to be manipulated. There may be disagreements about how to measure any of the relevant variables. And, finally, it may be extremely difficult, or even impossible, to isolate and manipulate all the variables suspected of being involved in the phenomena being studied.

Table 3. *A nonexhaustive list of journals reporting educational research relevant to teaching and learning physiology and the applications of this research in the classroom*

Learning sciences and cross-disciplinary journals
<i>Cognition and Instruction</i> (Erlbaum)
<i>Cognitive Science</i> (Elsevier)
<i>Educational Researcher</i> (American Educational Research Association)
<i>Journal of the Learning Sciences</i> (Erlbaum)
<i>Journal of College Science Teaching</i> (National Science Teachers Association)
<i>Journal of Research in Science Teaching</i> (National Association for Research in Science Teaching)
<i>Review of Educational Research</i> (American Educational Research Association)
<i>Science Education</i> (Wiley InterScience)
Disciplinary journals
<i>American Journal of Physics</i> (Wiley InterScience)
<i>Journal of Chemical Education</i> (American Chemical Society)
<i>Advances in Physiology Education</i> (American Physiological Society)
<i>American Biology Teacher</i> (National Association of Biology Teachers)

Norman (81) and Murray (74) have outlined some of the problems with doing research in medical education. The problems they identified are, of course, no different than those outlined by Berliner (8).

Evens and Michael (25) have discussed how these difficulties affected their studies of one-on-one human tutoring in cardiovascular physiology and their attempts to determine the effectiveness of a computer tutor operating in this same domain.

The consequence is that conclusions from “laboratory” educational experiments (where better control of the variables is possible) may appear quite robust, but results from “classroom” experiments (where all of the difficulties of controlling variables are present) may look much less robust and convincing. Furthermore, it is often difficult to transfer the findings of laboratory experiments to the classroom precisely because there are so many uncontrolled (and uncontrollable) variables in the classroom context. Finally, results from a particular student population (course, classroom, or institution) may not transfer well to a different context (course or class) for the same reasons.

It is also clear that there are significant problems with replicating experiments, more so for classroom experiments than for laboratory experiments. The reason for this is the fundamental difficulty of identifying and controlling those variables that may affect the outcomes of the experiment. If there are six variables that describe the system being studied, but you can only identify and control four of them, each time you attempt to replicate an experiment there is a high probability that the system you are studying now is different than the system on which the initial results were obtained.

It is fair to say, then, that the results of educational research are rarely as definitive as the results from physiology experiments. Nevertheless, as I hope this review has shown, there is an enormous wealth of research supporting the benefits of active learning in helping students master difficult subjects. Those of us charged with helping students learn physiology need to know about this research and incorporate the ideas from the learning sciences in our thinking about how we teach. I would also urge that we all think about what contributions we

can make to furthering the acquisition of knowledge about teaching and learning physiology.

How to Stay Abreast of Developments in This Field

Michael (57) has provided a list of education and other related journals that regularly publish articles relevant to life science education. Table 3 contains a partial listing of these journals. Matlin (50) has produced an annotated bibliography of books and articles on a number of topics related to college teaching in all disciplines, both science and nonscience.

It is obvious from the list of journals shown in Table 3 that many, if not most, of the professional science societies support and promote research and thinking about teaching and learning within their discipline (see Table 4). National (and sometimes regional) meetings of these societies can provide access to the latest results and thinking about issues related to teaching and learning. Conference proceedings (in some cases, published commercially) provide valuable archives of current work.

Conclusions

There is evidence that active learning, student-centered approaches to teaching physiology work, and they work better than more passive approaches. There is no single definitive experiment to prove this, nor can there be given the nature of the phenomena at work, but the very multiplicity of sources of evidence makes the argument compelling.

Therefore, we should all begin to reform our teaching, employing those particular approaches to fostering active learning that match the needs of our students, our particular courses, and our own teaching styles and personalities. There are plenty of options from which we can choose, so there is no reason not to start. This will mean that we too become learners in the classroom.

As scientists, we would never think of writing a grant proposal without a thorough knowledge of the relevant literature, nor would we go into the laboratory to actually do an experiment without knowing about the most current methodologies being employed in the field (59). Yet, all too often, when we go into the classroom to teach, we assume that nothing more than our expert knowledge of the discipline and our accumulated experiences as students and teachers are required to be a competent teacher. But this makes no more sense in the classroom than it would in the laboratory!

The time has come for all of us to practice “evidence-based” teaching.

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Table 4. *A nonexhaustive list of professional societies whose meetings feature research relevant to science teaching and learning*

American Educational Research Association
National Association for Research in Science Teaching
Cognitive Science Society
American Association of Physics Teachers
American Physiological Society
American Chemical Society

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REFERENCES

1. **Alexander PA and Murphy PK.** The research base for APA's learner-centered psychological principles. In: *How Students Learn: Reforming Schools Through Learner-Centered Education*, edited by Lambert NM and McCombs BL. Washington, DC: American Psychological Association, 1998, p. 25–60.
2. **Anderson JR.** *The Architecture of Cognition*. Cambridge, MA: Harvard Univ. Press, 1983.
3. **Arnaudin MW and Mintzes JJ.** Students' alternative conceptions of the human circulatory system: a cross-age study. *Sci Educ* 69: 721–733, 1985.
4. **Association of American Medical Colleges.** *Physicians for the Twenty-First Century, the GPEP Report*. Washington, DC: Association of American Medical College, 1984.
5. **Ausable DP.** *The Psychology of Meaningful Verbal Learning*. New York: Grune and Stratton, 1963.
6. **Barr RB and Tagg J.** From teaching to learning—a new paradigm for undergraduate education. *Change*: 13–25, 1995.
7. **Barrows HS and Tamblyn RM.** *Problem-Based Learning: an Approach to Medical Education*. New York: Springer, 1980.
8. **Berliner DC.** Educational research: the hardest science of them all. *Educational Researcher* 31: 18–20, 2002.
9. **Blumenfeld PC, Marx RW, Solloway E, and Krajcik J.** Learning with peers: from small group cooperation to collaborative communities. *Educational Researcher* 25: 37–40, 1996.
10. **Bossert ST.** Cooperative activities in the classroom. *Rev Res Educ* 15: 225–250, 1998/1989.
11. **Bransford JD, Brown AL, and Cocking RR (editors).** *How People Learn: Brain, Mind, Experience, and School*. Washington, DC: National Academy, 1999.
12. **Briscoe C and LaMaster SU.** Meaningful learning in college biology through concept mapping. *Am Biol Teacher* 53: 214–219, 1991.
13. **Burrowes PA.** Lord's constructivist model put to a test. *Am Biol Teacher* 65: 491–502, 2003.
14. **Chi MTH.** Commonsense concepts of emergent processes: why some misconceptions are robust. *J Learn Sci* 14: 161–199, 2005.
15. **Chi MTH, de Leeuw N, Chiu MH, and LaVancher C.** Eliciting self-explanations improves understanding. *Cog Sci* 18: 438–477, 1994.
16. **Chi MTH, Bassok M, Lewis MW, Reimann P, and Glaser R.** Self-explanations: how students study and use examples in learning to solve problems. *Cog Sci* 13: 145–182, 1989.
17. **Cohen EG.** Restructuring the classroom: conditions for productive small groups. *Rev Educational Res* 64: 1–35, 1994.
18. **Collins JW 3rd and O'Brien NP (editors).** *The Greenwood Dictionary of Education*. Westport, CT: Greenwood, 2003.
19. **Correa BB, Pinto PR, and Rendas AB.** How do learning issues relate with content in a problem-based learning pathophysiology course? *Advan Physiol Educ* 27: 62–69, 2003.
20. **Crouch CH and Mazur E.** Peer instruction: ten years of experience and results. *Am J Physics* 69: 970–977, 2001.
21. **Dougherty RC, Bower CW, Berger T, Rees W, Mellon EK, and Pulliam E.** Cooperative learning and enhanced communication: effects on student performance, retention, and attitudes in general chemistry. *J Chemical Educ* 72: 793–797, 1995.
22. **Driver R, Asojo R, Leach J, Mortimer E, and Scott P.** Constructing scientific knowledge in the classroom. *Educational Researcher* 23: 5–12, 1994.
23. **Eisenhart M and Towne L.** Contestation and change in national policy on “scientifically based” educational research. *Educational Researcher* 32: 31–38, 2003.
24. **Eisobu GO and Soyibo K.** Effects of concept and vee mapping under three learning models on students' cognitive achievement in ecology and genetics. *J Res Sci Teach* 32: 971–995, 1995.
25. **Evens M and Michael J.** *One-on-One Tutoring by Humans and Computers*. Mahwah, NJ: Erlbaum, 2006.
26. **Fisher KM, Wandersee JH, and Moody DE (editors).** *Mapping Biology Knowledge*. Dordrecht, The Netherlands: Kluwer, 2000.
27. **Gabel DL (editor).** *Handbook of Research on Science Teaching and Learning*. New York: Macmillan, 1994.
29. **Gardner M, Greeno JG, Reif F, Schoenfield AH, DiSessa A, and Stage E (editors).** *Toward a Scientific Practice of Science Education*. Hillsdale, NJ: Erlbaum, 1990.
30. **Glynn SM, Yeany RH, and Britton BK (editors).** *The Psychology of Learning Science*. Hillsdale, NJ: Erlbaum, 1991.
31. **Hake RR.** Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data for introductory physics courses. *Am J Physics* 66: 64–74, 1998.
32. **Halpern DF and Hakel MD.** Learning that lasts a lifetime: teaching for retention and transfer. *New Dir Teach Learn* 89: 3–7, 2002.
33. **Haskell R.** *Transfer of Learning: Cognition, Instruction, and Reasoning*. San Diego, CA: Academic, 2001.
34. **Heller P, Keith R, and Anderson S.** Teaching problem solving through cooperative grouping. Part 1: group versus individual problem solving. *Am J Physics* 60: 627–636, 1992.
35. **Hestenes D and Halloun I.** Interpreting the force concept inventory: a response to Huffman and Heller. *Physics Teacher* 33: 502–506, 1995.
36. **Hestenes D, Wells M, and Swackhamer G.** Force concept inventory. *Physics Teacher* 30: 141–158, 1992.
37. **Hintze TH and Zhao G.** Common misconceptions that arise in the first-year medical physiology curriculum concerning heart failure. *Advan Physiol Educ* 22: 260–267, 1999.
38. **One Hundred Seventh Congress of the United States of America.** *The Educational Sciences Reform Act of 2002 (107th Congress)*. Washington, DC: Congressional Act, HR 3801, 2002.
- 38a. **One Hundred Seventh Congress of the United States of America.** *No Child Left Behind Act of 2001*. Washington, DC: Congressional Act, Public Law No. 107-110.
39. **Johnson DW, Johnson RT, and Stanne MB.** *Cooperative Learning Methods: a Meta-Analysis* (online). <http://www.co-operation.org/pages/cl-methods.html> [21 August 2006].
40. **Johnson RT, Johnson DW, and Stanne MB.** Comparison of computer-assisted cooperative, competitive, and individualistic learning. *Am Educational Res J* 23: 382–392, 1986.
41. **Kind V.** *Beyond Appearances: Students' Misconceptions About Basic Chemical Ideas (2nd ed.)* (online). <http://www.chemsoc.org/LearnNet/rsc/miscon.pdf> [21 August 2006].
42. **Kutchai H.** *Reflections of a Medical School Teacher*. San Francisco, CA: Experimental Biology Symposium, 2006.
43. **Lake DA.** Peer tutoring improves student performance in an advanced physiology course. *Advan Physiol Educ* 21: 86–92, 1999.
44. **Lambert BL and McCombs NM (editors).** *How Students Learn: Reforming Schools Through Learner-Centered Education*. Washington, DC: American Psychological Association, 1998.
45. **Lemke JL.** *Talking Science: Language, Learning, and Values*. Norwood, NJ: Ablex, 1990.
46. **Limón M and Mason L (editors).** *Reconsidering Conceptual Change: Issues in Theory and Practice*. Dordrecht, The Netherlands: Kluwer, 2002.
47. **Lumpe AT and Staver JR.** Peer collaboration and concept development: learning about photosynthesis. *J Res Sci Teach* 32: 71–98, 1995.
49. **Massialis BG.** Discovery- and inquiry-based programs. In: *The International Encyclopedia of Education*, edited by Husen T and Postlethwaite TN. Oxford: Pergamon, 1985, p. 1415–1418.
50. **Matlin MW.** Cognitive psychology and college-level pedagogy: two siblings that rarely communicate. *New Dir Teach Learn* 89: 97–103, 2002.
51. **Mazur E.** *Peer Instruction*. Upper Saddle River, NJ: Prentice Hall, 1997.
52. **McCloskey M.** Naïve theories of motion. In: *Mental Models*, edited by Gentner D and Stevens AL. Hillsdale, NJ: Erlbaum, 1983, p. 299–324.
53. **McDermott LC and Shaffer PS.** Research as a guide for curriculum development: an example from introductory electricity. Part I: investigation of student understanding. *Am J Physics* 60: 994–1003, 1992.
54. **McGaghie WC, McCrimmon DR, Mitchell G, Thompson JA, and Ravitch MM.** Quantitative concept mapping in pulmonary physiology: comparison of student and faculty knowledge structures. *Advan Physiol Educ* 23: 72–81, 2000.
55. **McNeal AP and D'Avanzo C (editors).** *Student-Active Science: Models of Innovation in College Science Teaching*. Fort Worth, TX: Saunders College, 1997, p. vi.
56. **Mestre J (editor).** *Transfer of Learning From a Modern Interdisciplinary Perspective*. Greenwich, CT: Information Age, 2005.
57. **Michael JA.** Where to find the literature: an annotated bibliography of sources for life science education. *Ann NY Acad Sci* 701: 91–94, 1993.

58. **Michael JA.** Students' misconceptions about perceived physiological responses. *Advan Physiol Sci* 19: 90–98, 1998.
59. **Michael JA.** In pursuit of meaningful learning. *Advan Physiol Educ* 25: 145–158, 2001.
60. **Michael JA.** Mental models and meaningful learning. *J Vet Med Educ* 31: 1–5, 2004.
61. **Michael JA and Modell HI.** *Active Learning in Secondary and College Science Classrooms: a Working Model of Helping the Learning to Learn.* Mahwah, NJ: Erlbaum, 2003.
62. **Michael JA and Rovick AA.** *Problem Solving in Physiology (Instructor's Edition).* Upper Saddle River, NJ: Prentice Hall, 1999.
63. **Michael JA, Wenderoth MP, Modell HI, Cliff W, Horwitz B, McHale P, Richardson D, Silverthorn D, Williams S, and Whitescarver S.** Undergraduates' understanding of cardiovascular phenomena. *Advan Physiol Educ* 26: 72–84, 2002.
64. **Mierson S.** A problem-based learning course in physiology for undergraduate and graduate basic science students. *Am J Physiol* 275: S16–S27, 1998.
65. **Minstrell J and van Zee EH (editors).** *Inquiring Into Inquiry Learning and Teaching in Science.* Washington, DC: American Association for the Advancement of Science, 2000.
67. **Mintzes JJ, Trowbridge JE, and Arnaud MA.** Children's biology: studies on conceptual development in the life sciences. In: *The Psychology of Learning Science*, edited by Glynn SM, Yeany RH, and Britton BK. Hillsdale, NJ: Erlbaum, 1991, p. 179–202.
68. **Mintzes JJ, Wandersee JH, and Novak JD (editors).** *Teaching Science for Understanding: a Human Constructivist View.* San Diego, CA: Academic, 1998.
69. **Modell HI.** How to help students understand physiology? Emphasize general models. *Advan Physiol Educ* 23: 101–107, 2000.
70. **Modell HI and Michael JA.** Promoting active learning in the life science classroom. *NY Acad Sci* 701: 1–151, 1993.
71. **Modell H, Michael J, and Wenderoth MP.** Helping the learner to learn: the role of uncovering misconceptions. *Am Biol Teacher* 67: 20–26, 2005.
72. **Modell HI, Michael JA, Adamson T, and Horwitz B.** Enhancing active learning in the student laboratory. *Advan Physiol Educ* 28: 107–111, 2004.
73. **Modell HI, Michael JA, Adamson T, Goldberg J, Horwitz BA, Bruce DS, Hudson ML, Whitescarver SA, and Williams S.** Helping undergraduates repair faulty mental models in the student laboratory. *Advan Physiol Educ* 23: 82–90, 2000.
74. **Murray E.** Challenges in educational research. *Medical Educ* 36: 110–112, 2002.
75. **National Commission on Excellence in Education.** *A Nation at Risk: the Imperative for Reform.* Washington, DC: Government Printing Office, 1983.
76. **National Research Council Committee on High School Biology Education.** *Fulfilling the Promise: Biology Education in the Nation's Schools.* Washington, DC: National Academy, 1990.
77. **National Research Council Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century.** *BIO2010: Transforming Undergraduate Education for Future Research Biologists.* Washington, DC: National Academy, 2003.
78. **National Research Council Committee on Scientific Principles for Education Research.** *Scientific Research in Education*, edited by Shavelson RJ and Towne L. Washington, DC: National Academy, 2002.
79. **Niaz M, Aguilera D, Maza A, and Liendo G.** Arguments, contradictions, resistances, and conceptual change in students' understanding of atomic structure. *Sci Educ* 86: 505–525, 2002.
81. **Norman GR.** Reflections on BEME. *Medical Teacher* 22: 141–144, 2000.
82. **Novak JD.** Meaningful learning: the essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Sci Educ* 86: 548–571, 2002.
83. **Novak JD and Gowin DB.** *Learning How to Learn.* New York: Cambridge Univ. Press, 1984.
84. **Odom AL and Barrow LH.** Development and application of a two-tiered diagnostic test measuring college biology students' understanding of diffusion and osmosis after a course of instruction. *J Res Sci Teach* 32: 45–61, 1995.
85. **Pedersen S and Liu M.** Teachers' beliefs about issues in the implementation of a student-centered learning environment. *Educ Technol Res Dev* 51: 57–76, 2003.
86. **Perkins DN and Salomon G.** Transfer and teaching thinking. In: *Thinking: The Second International Conference*, edited by Perkins DN, Lochhead J, and Bishop J. Hillsdale, NJ: Erlbaum, 1987, p. 285–303.
87. **Prince M.** Does active learning work? A review of the research. *J Eng Educ* 93: 223–231, 2004.
88. **Quílez-Pardo J and Solaz-Portolés JJ.** Students' and teachers' misapplication of LeChatelier's principle: implications for the teaching of chemical equilibrium. *J Res Sci Teach* 32: 939–957, 1995.
89. **Rawson RE and Quinlan KM.** Evaluation of a computer-based approach to teaching acid/base physiology. *Advan Physiol Educ* 26: 85–97, 2002.
90. **Richardson D and Speck D.** Addressing students' misconceptions of renal clearance. *Advan Physiol Educ* 28: 210–212, 2004.
91. **Rivard LP and Straw SB.** The effect of talk and writing on learning science: an exploratory study. *Sci Educ* 84: 566–593, 2000.
92. **Romiszowski A.** The development of physical skills: instruction in the psychomotor domain. In: *Instructional-Design Theories and Models: a New Paradigm of Instructional Theory*, edited by Reigeluth CM. Mahwah, NJ: Erlbaum, 1999, vol. II, p. 457–481.
93. **Rovick AA and Michael JA.** The predictions table: a tool for assessing students' knowledge. *Advan Physiol Educ* 8: 33–36, 1992.
94. **Ryle G.** *The Concept of Mind.* London: Hutchinson, 1949.
95. **Savinainen A and Scott P.** Using the force concept inventory to monitor student learning and to plan teaching. *Physics Educ* 37: 53–58, 2002.
96. **Segal JW, and Chipman SF, and Glaser R (editors).** *Teaching and Learning Skills: Relating Instruction to Research.* Hillsdale, NJ: Erlbaum, vol. 1, 1985.
97. **Shaffer PS and McDermott LC.** Research as a guide for curriculum development: an example from introductory electricity. Part II: design of instructional strategies. *Am J Physics* 60: 1003–1013, 1992.
98. **Simon HA.** Learning to research about learning. In: *Cognition and Instruction: Twenty-Five Years of Progress*, edited by Carver SM and Klahr D. Mahwah, NJ: Erlbaum, 2001, p. 205–226.
99. **Sinatra GM and Pintrich PR (editors).** *Intentional Conceptual Change.* Mahwah, NJ: Erlbaum, 2003.
100. **Smith, JP III, deSessa AA, and Roschelle J.** Misconceptions reconceived: a constructivist analysis of knowledge in transition. *J Learn Sci* 3: 115–163, 1993.
103. **Svinicki MD.** A theoretical foundation for discovery learning. *Advan Physiol Educ* 20: 4–7, 1998.
104. **Tamir P and Zohar A.** Anthropomorphism and teleology in reasoning about biological phenomena. *Sci Educ* 75: 57–67, 1991.
105. **Towns MH and Grant ER.** "I believe I will go out of this class actually knowing something": cooperative learning activities in physical chemistry. *J Res Sci Teach* 34: 819–835, 1997.
106. **Van der Vleuten CPM, Dolmans DHJM, and Scherpbier AJJA.** The need for evidence in education. *Medical Teacher* 22: 246–250, 2000.
107. **Volpe EP.** The shame of science education. *Am Zoologist* 24: 433–441, 1984.
- 107a. **Vosniadou A and Ortony S (editors).** *Similarity and Analogical Reasoning.* Cambridge, UK: Cambridge Univ. Press, 1989.
108. **Walczyk JJ and Ramsey LL.** Use of learner-centered instruction in college science and mathematics classrooms. *J Res Sci Teach* 40: 566–584, 2003.
110. **West LHT and Pine AL (editors).** *Cognitive Structure and Conceptual Change.* Orlando, FL: Academic, 1985.
111. **Wilke RR and Straits WJ.** The effects of discovery learning in a lower-division biology course. *Advan Physiol Educ* 25: 62–69, 2001.
112. **Wosilait K, Heron PL, Shaffer PS, and McDermott LC.** Development and assessment of a research-based tutorial on light and shadow. *Am J Physics* 66: 906–913, 1998.
113. **Zohar A and Ginossar S.** Lifting the taboo regarding teleology and anthropomorphism in biology education—heretical suggestions. *Sci Educ* 82: 679–697, 1998.