Research on learning: potential for improving college ecology teaching

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Recent research has changed our understanding of how people learn. These findings are based on well-established learning theories that can potentially help faculty teach more effectively. Unfortunately, most science faculty, including ecologists, have little or no exposure to research on learning or its application to teaching. In this paper, four areas of research on knowledge and learning are given as the basis for an approach designed to help students overcome the common misconception that plants do not consume oxygen. To help improve college ecology instruction, ecology faculty and researchers who study learning should collaborate to design research about ecology teaching and ecological thinking.

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In 1999, the National Research Council published the highly anticipated book *How people learn: brain, mind, experience, and school* (Bransford *et al*. 1999), which shows how research on learning that is based on theory and experimentation can change teaching practice. The work on expert compared to novice learners is especially interesting. For example, one study contrasted how expert and novice chess players think about a chess game: while the expert classifies plays by category and can remember numerous similar moves at the end of the game, for novices the plays simply pass by in sequence, so they typically recall only the last few at the end (De Groot 1965). Related research shows that science experts tend to organize their thinking around a few big ideas (such as Newton's second law), which they use to solve problems, while novices rely more on memorization. These studies offer ideas about what "knowledge" is and how effective learners use it.

Research of this kind can potentially help faculty members teach more effectively (Smith and Anderson 1984; Mestre 1994; Tobin *et al*. 1994). Expert versus novice and other learning theories have implications for how teachers design a course, the type of questions they ask in class, and how they assess students' conceptual understanding of the material. These are all fundamental considerations for teachers.

In a nutshell:

- Recent research has deepened our understanding of how people learn
- Although most science faculty members know little or nothing about this research or its theoretical basis, it can be used to improve classroom teaching
- Ecology teachers and scientists who study learning need to work together to conduct research on ecology instruction

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How can ecology teaching benefit from this kind of research? How do ecology faculty members find out about education studies and theories, how students learn best, and which teaching practices work well and why? Unfortunately, most college ecologists (and biologists in general) have little exposure to research on teaching and learning. This is regrettable, because there are many valuable ways to apply learning theory to biology teaching (eg Lawson and Thompson 1988; Anderson *et al*. 1990; Lawson *et al*. 2000); some that are specifically relevant to ecology (eg Bishop and Anderson 1990; Hogan and Fisherkeller 1996) are presented in publications such as the *Journal of Research in Science Teaching*. However, few science faculty members, including ecologists, read education journals.

An ecology professor's ignorance of research on learning is akin to a tropical bird ecologists' ignorance about research on tree canopies. We would be appalled if a researcher never read journals in his or her field, or was unaware of fundamental hypotheses. Why aren't we similarly disturbed by professors who know nothing about research on learning or its application to teaching?

We should not single out ecologists; most science professors know little about research on science learning. My intention is to stimulate interest among ESA members about this issue. I will begin with an overview of cognitive/education theories, explore how research on learning could improve ecology teaching, and conclude with several suggestions for improving college ecology teaching.

■ A brief history of learning theories

Today, it seems natural that psychologists, neuroscientists, linguists, and anthropologists all study learning. Until the late 1800s, however, the study of the mind was left to theologians and philosophers. This changed at the turn of the 20th century, when the new school of behaviorism brought considerations of the mind into the domain of scientists (Figure 1).

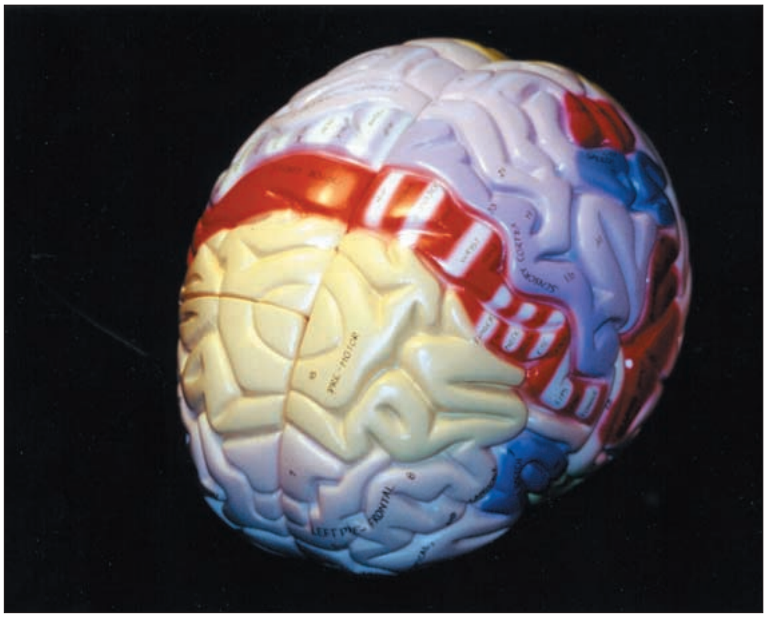


Figure 1. *Recent research on cognition and learning has changed our understanding of how people learn.*

Behaviorists view the mind as a "black box"; for them, "knowing" means observably connecting a response with a stimulus, and "learning" means making and strengthening those connections through reinforcement (or the reverse). Thus, a behaviorist might teach a caged animal to press a lever for food by initially rewarding the animal for simply turning towards the lever. Similarly, students will learn complex processes that are broken into component pieces and strung together, and then demonstrate their learning with a defined, desired behavior (Mestre 1994).

The behavioral approach does not take into account the cognitive aspects of learning (eg memory, reasoning, and thinking). The Swiss psychologist Jean Piaget championed the importance of cognition in the US in the 1960s, when he developed the concept of cognitive structures – patterns that change with age – by observing that similarly aged children make the same "mistakes" about the natural world. For instance, young children believe that things disappear when they are out of sight, and that big things sink and small ones float. Einstein, a contemporary of Piaget, was especially intrigued by children's claims that going faster takes more time.

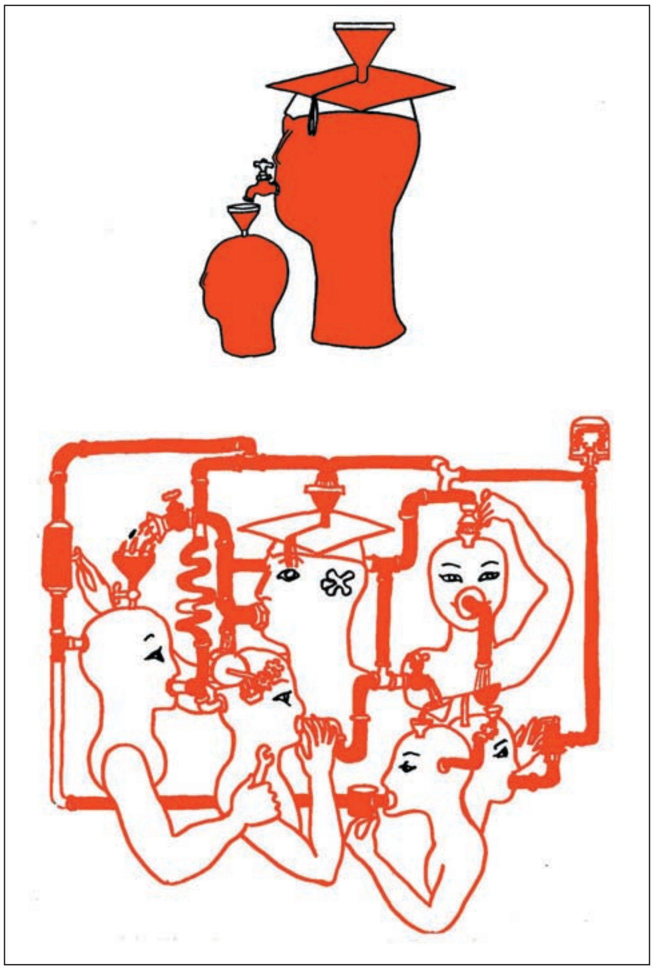
As they formed very different ideas about learning and knowledge from behaviorists, cognitive constructionists asked whether what was learned made sense to people. Constructivism relies on the belief that people actively construct their knowledge; constructivist teachers therefore reject the notion that students can assimilate exactly what they are taught. Moreover, because knowledge already in place is thought to affect our ability to learn new things, these teachers try to assess whether previously constructed ideas conflict with the information they want students to learn. Social constructivists further propose that learning is both cognitive and behavioral, that learning happens when people discuss and debate, and therefore that people create knowledge in a social setting (Steffe and Gale 1995). Their ideas are the basis for peer collaboration, a widely used method for involving students in their own learning (Figure 2).

■ Four related areas of research

Constructivism is the basis for four aspects of interrelated research on learning that have been particularly fruitful for educators.

Organizing knowledge

How experts organize and use knowledge, as compared to novices, has been an important research focus for physics educators (Dufresne *et al.* 1992; Mestre *et al.* 1992). For instance, Chi *et al.* (1981) gave experts and novices physics problems on index cards, which they were asked to sort according to principles or features they would use to solve the problems. More advanced



Courtesy Karl and Lila Smith

Figure 2. *Constructionist theories support the idea that students learn best by actively working together on problems and questions, not by passively receiving information given to them by their teacher.*

learners organized their cards by major concepts in physics (eg conservation of energy in a mechanics problem), while novices sorted by surface features (eg mechanics problems with inclined planes). Thus, novice learners did not recognize the concepts they could use to tackle the problems.

This expert/novice work is based on the existence of cognitive structures called "schema", and is therefore influenced by Piaget's ideas about cognition. Schema are thought to be "chunks" of recurring patterns of information (in physics, ideas and principles such as "conservation of energy") mentally arranged by the learner and readily accessible when needed.

Can research like that of Chi *et al.* influence classroom practice? Although studies are limited (Eylon and Linn 1988), there is some classroom research showing that it can. For instance, Dufresne *et al.* (1992) designed physics problems that constrained students to think about concepts and procedures "like an expert"; their research showed that this approach did increase students' ability to make more "expert-like" judgments as they worked on problems.

Student misconceptions

Addressing students' misconceptions (also called alternative or naive conceptions) is a related and important area of research in science education. Hundreds of studies show that students tenaciously hold onto erroneous, often predictable ideas that interfere with their ability to learn new concepts correctly. Constructivism forms the basis for research on misconceptions. Because constructivists believe that knowledge acquisition requires students to mentally restructure their own learning, they expect that students' understanding is often different from what teachers are attempting to teach.

Common misconceptions in ecology include students' understanding of photosynthesis, energy, food webs, evolution, and living versus nonliving things (Table 1). There are many ways teachers can reveal and then allow students to confront misconceptions. For instance, concept mapping – a method developed by Novak (1990) as a tool for organizing and presenting knowledge – exposes college students' misunderstandings of ecological phenomena (Okebukola 1990). Another avenue, which is more useful in large classes, is students' response to multiple choice questions specifically designed to highlight common misperceptions (Mestre 1994; Wenk *et al.* 1997).

The findings from misconception research on college biology and ecology students is quite discouraging. In one study, Anderson *et al.* (1990) used interviews and questionnaires to examine 100 college students, nearly all of whom had taken high school and college biology, on their understanding of photosynthesis and respiration. Most showed fundamental misunderstandings, believing for instance that plant roots were vaguely equivalent to animals' mouths. The authors found no relationship between the amount of biology a student had taken and his or her knowledge or understanding. The authors' conclusion that typical biology instruction leaves classic misconceptions unchanged has been confirmed in other studies of college biology and physics classes (eg Clement 1982; Nazario *et al.* 2002). However, other research, documenting the success of classroom approaches specifically designed to target misconceptions, is more encouraging (Eylon and Linn 1988).

Metacognition

Metacognition is a mental skill that students use to monitor their understanding, and could also be called "knowing what we know and what we don't know". It relies on self-teaching and other student-centered learning skills (Flavell 1979). For example, Schoenfeld teaches metacognitive skills using a group method that helps math students to be more aware of their thinking

Table 1. Common misconceptions in ecology and biology

Phenomenon	Misconception	Source
Photosynthesis	Plant roots are like animal mouths (plants take in all nutrients through their roots)	Anderson *et al.* 1990
	Plants get energy from soil and fertilizers in addition to the sun	Anderson *et al.* 1990
Respiration	Defined as people exhaling CO_2 and plants releasing O_2	Anderson *et al.* 1990
Food Webs	Only predator and prey populations affect each other	Griffiths and Grant 1985
	A population higher on a food web preys on all below	Griffiths and Grant 1985
	Organisms on lower trophic levels are there to serve ones higher up	Hogan and Weathers 2003
Evolution	Changes in traits are need-driven, so variations within a population or reproductive success are not important	Bishop and Anderson 1990
Ecosystems	Each component has properties identical to the whole	Hogan and Weathers 2003
	Both matter and energy are physical substances	Hogan and Weathers 2003

Misconceptions are erroneous, often predictable ideas that interfere with students' ability to learn new concepts correctly. Constructivist learning theories hold that we develop conceptions about the world based on our own observations, and that these "logical" ideas are therefore very hard to change.

processes (Schoenfeld and Herrmann 1982). As students work on problems in small groups, they are required to verbally address three questions: What exactly are you doing? (can you describe it precisely?); Why are you doing it? (how does it fit into the solution?), and How does it help you? (what will you do with the answer once you find it?). Schoenfeld also returns to these questions frequently during lectures.

There is evidence that this type of instruction can improve learning. Compared to control groups, Schoenfeld's students give more expert-like solutions to math problems. King (1992) also found that college students who had been taught self-questioning strategies were better learners, and retained information on exams longer than control groups.

Adult developmental stage theories

Various adult developmental stage theories describe how people's ideas about knowledge and the degree to which they turn to external authorities for "right answers" to complex questions advances with maturity (Kitchener and King 1981). A student with advanced epistemology (the nature of knowledge) in science knows, for example, how to evaluate controversies and about the existence of uncertainty.

William Perry is well known for his work on young adult development, based on his studies of Harvard students (1970). He was particularly interested in the interaction between personal agency (the degree of reliance on outside authority) and epistemology. According to Perry, students pass through stages of dualism (thinking there are "right" and "wrong" answers) and multiplicity (thinking one answer is as good as another) to relativism (thinking different opinions or outcomes may result from factors such as different assumptions or judgments). While students in the dualistic stage believe that external authorities can tell them the right answers to questions, more mature students trust their own ability to make decisions. The students Perry studied tended to be dualistic thinkers when they entered college and only reached the more mature stages after graduation. Piaget's influence on Perry's work includes the recognition that learning and development follow a linear sequence, and that learning is stage-driven.

Adult developmental theories form the basis for teaching practices that are designed to encourage students to question assumptions and not to take information at face value. These include inquiry-based teaching (D'Avanzo and McNeal 1997; Figure 3) and problem-based learning (PBL) (Wilkerson and Gijselaers 1996). Even though PBL is used in many medical schools and undergraduate courses, including ones with very large enrollments (Allen *et al.* 1996), research documenting its success is limited (Stage *et al.* 1998). As with PBL, few researchers have studied the effects of inquiry teaching on student learning. For this reason, Wenk's (2000) pre–post research, which shows substantial gains in epistemology and justification for students in inquiry-based science courses (as opposed to comparison students), is particularly intriguing.

■ Applying theories about learning to ecology teaching

Theories about learning can be the foundation for practices designed to improve student learning in ecology courses. Many beginning ecology and biology students believe that plants do not use oxygen (Anderson *et al.* 1990). This misconception points to a fundamental lack of understanding about respiration and energetics. If students don't recognize that plants produce and use oxygen, they cannot truly understand core ecological topics such as the role of oxygen in cell metabolism.

How can a professor help students to recognize and change this misconception? As an example, I will describe a five-step scenario that can be incorporated into any course, even with hundreds of students in a lecture hall. This example has been studied in numerous college biology courses (Ebert-May *et al.* 1997). Here it illustrates how a process deemed successful by classroom assessment (Mestre *et al.* 1992; Lumpre and Staver 1995; Ebert-May *et al.* 1997) is based solidly on constructionist theories. It is also an example of a learning cycle-type approach (Lawson *et al.* 1989), because students first engage in an investigation before they are formally introduced to a scientific concept (Panel 1).


Courtesy of P Harmon

Figure 3. *It makes sense that students learn scientific inquiry when they do their own field or laboratory research. However, adult development and expert/novice learning theories can also inform teaching practices that help students improve their scientific inquiry and critical thinking skills in courses, even those with large enrollments.*

Panel 1

Step 1: The professor projects Figure 4 and tells students that the data are measurements of oxygen concentrations over time in a light-tight bell jar containing a living plant. He/she explains that the plant was put in the jar at time zero, describes the relative proportion of the plant and jar, and so on.

Step 2: Students are asked to "turn to their neighbors" and discuss Figure 4 – specifically, whether they think that the oxygen concentration would increase, decrease, or stay the same, and why. They have 5 minutes to discuss these options with the students around them (D'Avanzo 2001).

Step 3: The professor rings a bell and asks the students to hold up colored cards for their chosen option (blue for "increase", etc). He/she reports the approximate vote distribution and asks for volunteers to explain each choice. He/she welcomes both simple and complex questions, paraphrases key points, and encourages participation by giving students time to talk and by joking with them. The atmosphere is both serious and upbeat, and most students appear engaged.

Step 4: Students once more discuss the three choices with their neighbors and vote again. If most select the correct answer and appear to understand their reasoning, the professor moves on. If not, more time is devoted to discussing this topic.

Step 5: Homework or an on-the-spot quiz tests the students' understanding. From a description of a related situation, students show likely results with simple, hand-drawn sketches of oxygen change with time. For instance, students learn about coral bleaching and zooxanthellae, and answer questions about how coral bleaching changes oxygen dynamics with time (see Panel 2).

Expert thinking

This exercise is designed to help students "think more like an ecologist" when they identify, talk about, and apply core ecological concepts and information – in this case, respiration. Thus, students behave as ecologists when they examine the oxygen data and match their reasoning with that of their peers. Working with and analyzing ecological data is also central to the final assessment step, because students must create their own graphs and explain the reasoning behind them (D'Avanzo 2000).

It is important for teachers to acknowledge that interpreting and applying data in this way are sophisticated skills that require practice and a good deal of time. The plant-respiration exercise might well take a full hour of a class session. Its use is based on the "less is more" idea – less material is covered, but more is retained (Sutman 1992).

Misconceptions

The exercise is designed to highlight and change the idea that plants in the dark do not consume oxygen, and is based on the assumption that students will come face to face with their misconceptions as they try to explain their thinking, answer questions, and listen to the reasoning of their peers. The predicted outcome is that students who recognize and discuss their "error" will retain the information that plants respire, as students working collaboratively have successfully done with misconceptions about photosynthesis (Lumpe and Staver 1995).

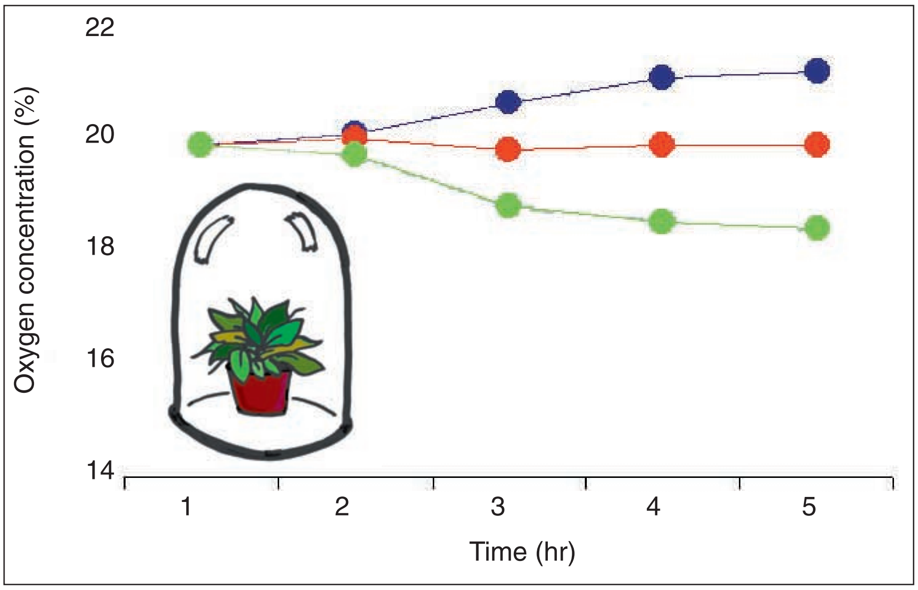


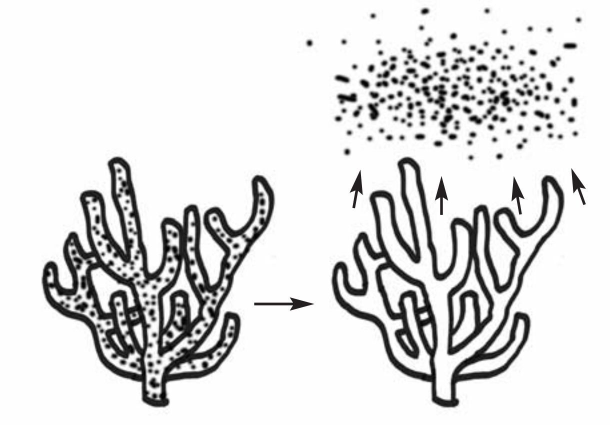
Figure 4. Classroom research shows that students can overcome common misconceptions when they work with other students on problems such as this. In this exercise, students are asked whether a plant in the dark increases, reduces, or does not change the oxygen concentration in a bell jar.

Metacognition

Like students in Schoenfeld's math class, students discussing the plant–jar question may become more aware of their own thinking when they share their reasoning with peers. Faculty members can encourage metacognitive thinking by coaching students to ask each other ques-

Panel 2. An authentic assessment of students' understanding of photosynthesis and respiration. According to current theories about learning, assessment is not something that happens at the end of a lesson; it is a tool for learning the lesson.

Early naturalists debated whether corals were plants or animals. We now know that photosynthetic organisms called zooxanthellae live in the outer cells of corals, an example of symbiosis ("living together") in which both the coral animal and the zooxanthellae benefit. Coral bleaching, a phenomenon that is occurring in reefs worldwide, may be a result of global warming. During bleaching events, corals eject their zooxanthellae into the ocean (it is unclear why). Since the zooxanthellae's dominant photosynthetic pigments are brown, the corals look white when they are gone.



Imagine an experiment in which pieces of unbleached coral were put into three aquariums and bleached coral into three other aquariums. The number of coral pieces and species are the same. Sketch a simple X-axis/Y-axis graph (the type we have been discussing in class), showing change of oxygen with time in the two sets of aquariums. You will not be graded on your drawing ability. However, the figure must be clear and easy to interpret, so you should label all important aspects. In addition, in two paragraphs briefly write a description and interpretation of the figure, in no more than 150 words.

tions, such as: "Why do you say that? What is your reasoning?" or "How is this idea different from your earlier one?". Similar questions during full class discussions will reinforce these critical thinking skills.

Adult developmental theory

In this exercise, developmental theory comes into play when students ask questions, especially deeper, more interesting ones. For instance, a student might wonder about a plant put in shade as opposed to the dark – would the oxygen concentration in the jar stay the same? (This student would have invented the idea of compensation point.) Other students listening to this question might then appreciate how modest changes in experimental design can greatly affect results – an epistemological realization. Moreover, naive students might never think of changing the given conditions or even realize that they could ask interesting scientific questions (external vs internal agency). Simply encouraging students to be curious and ask open-ended questions changes their perception of themselves as scientific thinkers (Wenk 2000).

■ Collaboration between learning researchers and ecology faculty

Introductory ecology is taught in thousands of ecology and biology courses, so the impact of improving ecology teaching could be far reaching. There is some evidence that a reform of college ecology is needed – that ecology faculty members, like their colleagues in other scientific disciplines (eg Walczyk and Ramsey 2003), still rely on traditional teaching tactics. A recent survey of Ecological Society of American faculty showed that most introductory-level biology and ecology teaching is not based on current thinking about how students learn best. Most classes (90%; $n = 131$) depend heavily on passive lecture; open-ended labs are rare in majors' introductory biology courses (10%), and many students never go outside to study ecology in introductory courses (34% ecology, 17% biology) (Brewer 1998).

How can we fundamentally change ecology faculty member's thinking about teaching and learning? Clearly this will require a variety of tactics. One facet that is essential and potentially far-reaching is research on ecology teaching, which could result from a collaboration between ecology faculty members and scientists who study learning. Ecology educators, ecology researchers, and cognitive scientists should therefore work together to design research about ecology instruction and ecological thinking.

Such collaborations have happened in other sciences. For instance, computerized visualizations of molecules are potentially powerful teaching tools, but chemistry teaching staff were unsure how to use them. By observing chemistry students, education researchers were able to suggest better ways to help students make the link between these symbolic images and the abstract concepts they are designed to illustrate (Kozma and Russell 1997). In contrast to chemists, few ecology teachers have worked with learning researchers. Perhaps this is because ecology educators have not clearly defined ecological "ways of thinking and knowing" that are unique or especially important in our discipline (Picket *et al.* 1994). Possibilities include space for time thinking (as in assuming that different patterns across a landscape represent different time periods) and systems thinking (Hogan and Weathers 2003). Cognitive scientists, like all researchers, must be personally drawn to an area of inquiry before they become

Table 2. Learning theories and their application to teaching: some helpful introductory references

Source	Theory
Kurfiss 1988	Learning theories related to teaching critical thinking
Gabel 1994	Introduction to research on science teaching and learning
Stage *et al.* 1998	Application of learning theories to "learning-centered" teaching
Bransford *et al.* 1999	New developments in the science of learning
Uno 2002	Includes section on how students learn
Colburn 2003	Concise discussion of education terms and ideas
D'Avanzo in press	Application of theories about metacognition to ecology teaching

willing to devote time to it.

Of course, research on ecology teaching will not influence classroom practice unless faculty members can easily learn about the research and its foundations and are motivated to do so (Table 2). Reading journals is a traditional way to learn about research, but science teachers rarely read education journals. One way to address this conundrum in ecology is for the flagship journals to publish ecology education research. While this has not been the case in the past, the situation is changing. For example, *Ecological Applications* has expanded its focus to include ecology education research ("[Since] there is increasing interest in education within the science of ecology . . . papers on educational topics . . . may be considered for publication") (Schimel 2002). *Frontiers* is another ESA journal that publishes education articles.

Still, easy access to research on learning will probably not matter to ecology educators unless they see teaching reform as important. Both motivation and time are issues. There is no getting around the fact that improving a course takes time, which means not doing something else. Regarding motivation, Walczyk and Ramsey's (2003) research shows that even faculty members who willingly participate in teaching workshops must be very determined to fundamentally change their teaching. They must educate themselves about learning theories (Table 2), be open-minded about what constitutes good teaching, and update their knowledge through workshops and journals. However, as numerous articles and reports have pointed out, they will not make this considerable effort unless they are rewarded financially, and in tenure and promotion decisions (Boyer 1990; George 1996).

Despite these difficulties, ecology teaching can still benefit from research on learning. For this to happen, ecology educators must seriously consider what it means to teach and learn ecology, and then seek out colleagues who will stretch their thinking and collaborate on research. We ecology professors really should do this. Our students deserve it.

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