The Current Status and Future Direction of Biology Education Research

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Clarissa Dirks, Ph.D., The Evergreen State College

I. Introduction

Practitioners of discipline-based education research (DBER) aim to improve teaching and learning in science, technology, engineering and math (STEM) disciplines. Science instructors frequently confront discipline-specific challenges when helping students overcome misconceptions and achieve deep conceptual understanding in STEM fields. In response to these problems, some practicing scientists and science instructors have gained knowledge about teaching and learning from cognitive research and are now conducting controlled, discipline-based studies in their own classrooms. For more than 30 years, physicists have conducted DBER, varying pedagogical methods to determine the influence on student learning. However, it has only been relatively recent that a good number of scientists in other STEM disciplines have engaged in DBER. Undergraduate biology education research (BER) is probably the most recent DBER field to have emerged. In the last decade, a large number of BER publications and several biology concept inventories have been produced [1-5]. The focus of this paper is to summarize the contributions of undergraduate BER from the past twenty years, as well as discuss the limitations in the research and future directions of the field.

II. Methodologies

An extensive search to identify BER studies about student learning of biology concepts, student attitudes or beliefs toward learning biology, and the development or use of validated assessment instruments to measure student performance in biology resulted in the initial collection of over 350 journal articles, reports, and websites. The search focused on studies done in the past twenty years and included many sub-disciplines of biology: microbiology, neurobiology, genetics, genomics, cell and molecular biology, ecology, evolution, and physiology. For exceptional articles, biochemistry and medical education were also included. Searches were done using ERIC, ERIC Ovid, PubMed, Google Scholar, the University of Washington library electronic database, as well as agency and journal websites. Appropriate BER articles were identified using “biology” in combination with a variety of terms such as “student performance”, “learning”, “attitudes”, “concept inventories”, and other related words. The search was subsequently restricted by selecting “post-secondary”, “higher education” and “undergraduate” categories when applicable. Several criteria were used to determine if an article or resource would be included in the final analysis, and with few exceptions, integrated articles were about studies that:

- were published between 1990-2010
- reported quantitative or qualitative data about student learning, performance, or attitudes in undergraduate biology (2-year colleges included)
- reported quantitative or qualitative data about instruments used for measuring student learning or attitudes in undergraduate biology (2-year colleges included)
- provided an extensive overview of BER or BER assessment tools at the undergraduate level

Conference proceedings and reports were also included if the source was peer reviewed and met the criteria for articles. Websites were included only if they provided a reviewed tool or resource and those findings were reported in other BER articles.

Using the designated criteria for BER studies, 195 case items were identified. The majority (86%) are articles from 62 different peer-reviewed journals, while the rest are peer-reviewed conference proceedings, reports, and websites. Twelve items are broad overviews that provided extensive information about BER, BER studies, assessment strategies in biology, concept inventories, or validated tools for BER studies. The majority of the items (83%) were published in 2001-2010, indicating a notable increase in the number of BER studies in the last decade. A full list of resources, including journals, the number of case items per journal, and the years published can be found in Appendix A.

Three main categories were used to organize BER studies into groups for further analyses.

1. Student learning or performance. BER studies that investigated student-centered approaches in the classroom or laboratory (active learning and inquiry based labs), methods to enhance or deliver the learning experience outside the classroom (supplemental instruction and web-based instruction), how students learn biology (misconceptions, metacognition, domain specific learning, and science process skills), how undergraduate research impacts students, and how particular groups (underrepresented and others) perform in biology are groups within this category.

2. Student attitudes and beliefs. Groups within this category include studies about student motivation for learning biology, approaches to learning biology, and studies that explored how students' beliefs impact learning of biology.

3. Concept inventories and validated instruments. Two groups of studies fit into this category: studies that described the development and testing of instruments for measuring student learning or attitudes, and those that were designed to measure some other aspect of learning, such as engagement.

The three categories of BER studies were analyzed separately because they are inherently very different from one another with respect to goals and methods. The dependent variables for categories 1 and 2 were student achievement or attitudes after a particular treatment (independent variables, such as a teaching strategy, curriculum, or undergraduate research experience). Each study within a group was analyzed for characteristics such as the kinds of questions addressed, years and settings in which the study took place, length of study, and methods used to collect data. Although many BER studies in categories 1 and 2 tested multiple treatments and collected different kinds of data, they were categorized and analyzed based on their main focus. However, if the study provided substantial evidence in two or more areas, those findings were often analyzed and discussed in those areas as well. Study characteristics for category 3 (concept inventories and validated instruments) included the year in which the tool was developed, the target content area and whether or not the tool had been tested for reliability and validity. The following section presents a detailed analysis of the characteristics for each category, as well as a description, theoretical frameworks and major findings of groups within that category. For all categories, reviews were excluded from the quantitative analyses.

III. Characteristics, Descriptions, Theoretical Frameworks, and Major Findings

Category I: Student Learning or Performance

Characteristics

Studies that compared the results of treatment and control groups, or those that compared groups receiving varying treatment, were considered “controlled” studies; most of the studies analyzed in this paper were quasi-experiments, lacking complete randomization. Studies were classified as having a positive impact if they showed learning gains using pre- and post-tests (administered as independent assessments or imbedded within summative assessments) or other gains, such as differences in scores on an identical exam administered to control and treatment groups. Any study that showed self-reported gains were noted, even if they also collected the kinds of quantitative data described above. The percentage of studies having these and other characteristics can be found in Table 1.

Table 1. Characteristics of BER Studies – Category 1							
Group % from 2001-10 (N) citations	**Average length of studies in semesters***	**% studies done with only majors**	**% studies done in lower division courses**	**% studies done in a course setting**	**% studies measuring achievement by URM or gender**	**% studies with controls or comparison groups**	**% studies having a positive impact (SR)†**
Active Learning╪ 80% 2001-2010 (N=69) [6-55][56-72]	2.3	80%	84%	84%	11%	90%	91% (97%)
Inquiry-based Labs 100% 2001-2010 (N=15) [73-87]	2.0	87%	87%	80%	7%	47%	53% (100%)
Supplemental Instruction 100% 2001-2010 (N=6) [88-93]	3.3	83%	83%	83%	33%	50%	83% (100%)
Web/Technology-Based Instruction 93% 2001-2010 (N=15) [88-108]	2.1	93%	60%	80%	0%	73%	20% (87%)
Misconceptions & Metacognition 78% 2001-2010 (N=9) [109-116]	1.1	78%	78%	67%	0%	33%	100% (N/A)┼
Science Process Skills 100% 2001-2010 (N=11) [19, 117-127]	2.5	100%	63%	91%	9%	45%	45% (82%)
Domain Specific 100% 2001-2010 (N=4) [128-131]	2.7	100%	75%	50%	25%	25%	75% (N/A)
Undergraduate Research Experience 86% 2001-2010 (N=7) [132-138]	7.3	N/A	N/A	14%	57%	57%	28% (100%)
Underrepresented Groups 100% 2001-2010 (N=6) [19, 139-143]	10.3	100%	N/A	50%	100%	83%	83% (100%)

* Studies based on the quarters were treated as semesters for data analysis, albeit most were reported as semesters

† Studies having a positive impact reported learning gains from pre- and post-tests, exam scores, grades, retention, etc…; self reported (SR) gains in knowledge or skills were also considered in this analysis

┼ Studies that did not include self reported gains were not applicable (N/A), as were those groups having insufficient or mixed data analyzed here

╪ Of these active learning studies, 26% also measure that students had a positive response to the teaching strategy

The predominant source of data collected for the studies analyzed was quantitative, albeit studies investigating the impact of undergraduate research experiences or studies of underrepresented groups often presented interview or survey data. Most studies reported learning gains from pre- and post-tests, exam or quiz scores, or course grades. It should be noted that those reporting learning gains rarely used validated instruments or presented their assessment tools in the publication. Less common were studies that presented other kinds of data such as incoming SAT scores, high school GPA, college GPA, retention within a major, and graduation rates. However, these kinds of data were often found in studies on the performance of underrepresented groups. More than half the studies in this category collected qualitative data based on surveys, interviews and course evaluations; in some cases the overall results were based on student self-reported data.

<u>Descriptions</u>

Active Learning

Active learning is a student-centered approach to instruction requiring students to engage in meaningful learning activities, particularly in the classroom. An individual or group can participate in active learning but it always requires learners to be mentally and physical active while gathering information, assessing what they know, and problem-solving. Active learning is in direct contrast to expository instruction, which is typically characterized by passive transmission of information from the instructor to the student [31].

Active learning encompasses many different approaches such as cooperative or collaborative learning, problem-based or case-based learning, group work, think-pair-share, peer instruction, inquiry-based learning, technology-enhanced learning, and concept mapping [144].

- Cooperative learning is characterized by activities that require mutual interdependence, significant interaction, and actions related to cooperative outcomes rather than competition. Studies showing the effectiveness of this approach in biology and other

STEM disciplines have been well document [2, 144-147]. Group work, think-pair-share, and peer instruction are cooperative learning activities.

- Collaborative learning refers to instruction that involves students working together toward a common goal with outcomes assessed based on group work [144]. This is in contrast to cooperative learning which entails group work but students are assessed as individuals [148].
- Problem-based learning is a method characterized by students solving contextual problems that motive learning of content – this kind of learning can be done by individuals or in groups. Problem-based learning is often distinguished from case-based learning in that the problem is first presented to the learner prior to instruction on the concepts fundamental to solving the problem [149]. In case-based learning, students must have already acquired a basic understanding of the scientific principles in order to work with the problem [60].
- Inquiry-based learning provides students with an authentic scientific experience requiring students to pose questions, confront their misconceptions, develop hypotheses, and design experiments to test them [31].
- Technology-based learning is a contemporary method for delivering or enhancing instruction using podcasts, animations or other methods. The impact of these methods on student learning in biology has not been well studied [103] and will be further discussed in the context of web-based instruction. It is important to include this here because many instructors are supplementing their instruction with web-based activities.

Supplemental Instruction

Supplemental instruction (SI) arranged as a separate class or through a web interface has proven to be an effective method for enhancing learning in biology, particularly for underrepresented groups [19, 88-93, 139, 141]. SI courses are structured in various ways but typically include opportunities for students to work in a cooperative manner solving problems related to course content. In some cases, study skills of participants are augmented by explicit instruction in diagramming questions or implementing methods to help students develop metacognitive skills [119].

Web-based Learning Strategies

Web-based strategies and other kinds of technology are becoming increasing useful for enhancing learning of biology. There are numerous ways in which technology is being used: podcasts, animations, multimedia instruction, digital libraries, virtual labs and peer review are just a few of the many examples. Because biology is a discipline readily amenable to visual representations, many are using animation tutorials and other tools such as Cn3D to enhance learning of biology [64, 99, 103, 104, 106-108].

How Students Learn Biology

BER studies that focused on how students learn biology fell into four main categories: misconceptions, metacognition, science process skills, and domain specific learning.

Because no two students are the same, they come to biology classes having a wide variety of preconceptions based on their prior experiences. In some cases those preconceptions are misconceptions that impede learning of new concepts [150, 151]. Many science education researchers have become very interested in identifying students' misconceptions and developing teaching strategies that help students to work through them. Indeed, most concept inventory tests in biology incorporate common misconceptions as multiple choice distractors for this reason [1, 152-156].

Metacognition – the self-identification of a learning goal and the subsequent monitoring of progress in achieving that goal – is a critical skill for effective learning in any area [150]. Because metacognition is essential for adaptive transfer of knowledge [157], it is critical that students are given opportunities for self-directed learning [158]. Although this key principle has been well documented in the K-12 literature [115], there is scarcity of BER studies about student metacognition at the college level.

Science process skills, such as the ability to interpret graphs or data, pose testable hypothesis, design experiments, and communicate science effectively, make up the conceptual framework of scientists. Therefore it is not surprising that acquisition of science process skills can have a profound impact on student success in college science classes [19, 32, 117, 119, 122, 126]. Research in this area examined if explicit instruction of science process skills augmented student learning of biology.

Studies that focus on how students learn a sub-discipline of biology or a particular biology topics are referred to as domain-specific studies and employ a wide-variety of strategies depending on the question investigated. There many descriptive articles about domain-specific teaching and learning strategies but very few that measured learning gains or other important information to indicate if the strategy worked.

Undergraduate Research Experiences

Undergraduate research experience is an important educational component for biology students and numerous studies have cited the benefits [133, 135, 138]. Studies that focused on how undergraduate research experiences help shape students' career goals or enhanced their understanding of science fell into this group.

Improving the Success of Underrepresented Groups

This section describes studies that specifically aim to identify strategies, or measure the outcomes of a strategy, to improve success of underrepresented groups (underrepresented minorities, women, economically disadvantaged students, and first generation students) in the biological sciences.

<u>Theoretical Frameworks</u>

Most studies did not explicitly state the theoretical framework under which the research took place, but rather described a problem that the research addressed. When present, the most common references were to those implementing “cooperative” or “constructivist” approaches, particularly studies about active learning. Cooperative learning is based on the social interdependence theories of K. Lewin [160] and deeply rooted in work of J. Dewey [161] which supports experiential learning. The term “constructivist” was frequently used because active learning is based on constructivism, whereby people acquire new knowledge through interactions of their ideas and experiences; constructivism began with the work of Jean Piaget and was further developed by David Ausubel and John Dewey [5, 162-165]. For other studies about group work, stereotype theory [159] and its role in group work during biology classes was mentioned. Along these lines, studies about conceptual change focused to identifying student’s misconceptions about biological processes because students must first address their misconceptions in order to correctly construct new concepts [150].

Studies about inquiry based labs, students’ acquisition of science process skills, and undergraduate research experiences utilize another constructivist approach – the learning cycle [166, 167]. In the learning cycle, students pose questions, confront their misconceptions, develop hypotheses, and design experiments to test them [31]. Although studies did not specifically discuss the learning cycle and often referred to the research as being based on “inquiry” or “guided inquiry” approaches, they all described how their teaching methods were intended to engage students in scientific processes similar to those experienced by scientists, thus mirroring the learning cycle. Successful implementation of these methods was measured as a positive impact on students’ attitudes about doing science and their competency for implementing science process skills.

Major Findings

By far, the most common BER studies in the past 20 years were based on implementing active learning strategies and determining the outcomes of such treatments on student learning. In the late 80s, Thomas Lord began conducting controlled studies to determine if students performed better on assessments if they engaged with the content through active learning [37].

He continued to perfect his methods and published compelling findings that active learning improved student learning in an environmental science course [168]. In 2003, Patricia Burrowes put “Lord’s Constructivist Model” to the test [10]. She taught two introductory biology courses: one course was taught in a traditional style (control group) with lectures, quizzes and exams, whereas the other was taught in an experimental fashion – students worked daily in groups of four to solve problems and evaluate each other’s work. At random she selected groups to present their answers to the class and groups (25% of the class) that would have to stay for a quiz at the end of the class. Students in the experimental group had significantly higher scores on all three exams and attained significantly higher final grades in the course than students in the control group [10]. Pre- and post-assessment of students’ attitudes about learning biology showed that more students in the experimental group increased their interest in biology by the end of the course compared to those in the control group [10].

Frequent assessment (graded or non-graded) in combination with active learning significantly improves student performance in biology [10, 14, 23, 34, 35, 54]. Biology instructors are widely adopting the use of personal response systems, or “clickers”, in their classrooms. These devices provide students with instant feedback about their learning as well as excellent opportunities for cooperative peer instruction. In general, students in interactive classrooms where clickers are employed show increased learning gains and higher exam scores than those taught in traditional classrooms [13]. Most notably, it has frequently been observed that the percentage of students who earn less than approximately 60% of total points in a course significantly decreases with the use of clickers [13, 23, 35, 49]. For example, a study by Knight and Wood showed that by replacing 30% of traditional lecture time with multiple choice clicker questions students had significantly greater learning gains on identical multiple choice diagnostics and total course points compared to students taught in a traditional manner [35]. These kinds of BER studies are becoming more common, likely due to the relative ease with which clicker questions are implemented into classrooms. The clicker revolution has prompted many researchers to further investigate the ways in which peer discussion, or the order in which data is presented to the learner, influences learning in biology [51, 61].

Several groups have shown that collaborative learning, particularly collaborative testing, improves student retention of content knowledge [18, 58, 71]. Cortright, et al. implemented a cross over design in which half the students first completed exams as individuals and then as groups, followed by retesting as individuals four weeks later. The other half of the students did all activities as individuals for that exam, but acted as the experimental group for the following exam. In both groups, students who participated in collaborative testing performed significantly better on retests than students who had repeated the exam as individuals [18]. Thus, retention of knowledge is improved with collaborative work.

Numerous studies in biology and other STEM disciplines have shown similar results to ones presented here; it is conclusive that active learning works [169]. There are even new instruments to assess the percentage of time students are actively engaged in the classroom [170]. Given the overwhelming evidence that active learning improves learning in science, it should no longer be referred to as a pedagogical practice, but rather it should be considered the central dogma of science education.

Supplemental Instruction

Rath et al., Barlow et al., and Dirks and Cunningham have all shown that freshman who participate in SI courses have higher overall grades in subsequent biology courses, greater persistence as biology majors, and higher graduation rates than students in the same curricula who do not participate in SI [19, 90, 139]. Most importantly, in all cases underrepresented minorities and women benefit the most. SI can also come in the form of “boot camps” which are courses students take at the beginning of their college experience. The Biology Intensive Orientation for Students (BIOS) program at Louisiana State University is an intensive prefreshman program for students intending to be biology majors; the course introduces some biology topics and provides instruction on study skills and learning styles [93]. Compared to a control group, students who participated in BIOS performed significantly better in their biology classes and graduated at higher rates [93]. In summary, SI courses enhance student performance by preparing incoming freshman for college and providing them with a network of students who will participate in cooperative learning.

Web-based Learning Strategies

O'Day conducted a controlled study in an upper-division biology course where particular topics were presented in two ways: the treatment group used animations to learn, whereas the control group used simple graphics [106]. Students who learned the content using animations scored higher on pre- and post-tests than did the control group; the experimental group also showed greater long-term retention of the material [106].

McFarlin substituted 50% of his lectures with online instruction; the online lectures were PowerPoint presentations with audio and students had the option to watch animations. Students were required to take quizzes after each lecture. Throughout the three year study, students who participated in this hybrid course performed significantly better on identical exams and earned higher overall course grades than students who were taught the same material in a traditional lecture format [104]. In the electronic age entire courses and hybrid courses in biology will be offered more frequently, thus it is important that the BER community continues to investigate how students learn in these formats.

How Students Learn Biology

In an attempt to break the cycle of perpetuating misconceptions, N. Pelaez, et al. designed a method to identify common misconceptions about physiology held by undergraduate biology students who are prospective elementary teachers [113]. She and her team also developed teaching tools to help students overcome their misconceptions. At the end of the course they found that many students still had erroneous ideas about human blood circulation and gas exchange – ideas that were only found through drawings and interviews, not exams

[113]. Findings from this study illustrate how deeply rooted misconceptions can be and point to future directions for biology education researchers.

Although there are only a few studies about developing undergraduate biology students' metacognitive skills, one Australian study exemplifies the importance of providing students with opportunities and guidance in developing metacognitive skills. McCrindle and Christensen randomly divided their introductory biology class into treatment and control groups; the treatment groups kept a journal about their learning processes throughout the course, whereas the control group wrote scientific reports about the content they were learning. By the end of the course, students in the treatment group demonstrated more sophisticated learning strategies when presented with a task and performed better on exams than the control group, even though the control group spent more time with the content [111].

At the University of Washington, freshman who participated in a course in which they were explicitly taught science process skills prior to taking biology earned, on average, higher overall grades in all three introductory biology courses compared to students who did not participate in the program [19, 119]. Kitchen et al. redesigned their biology course to explicitly teach their students data analysis and interpretation skills. Students in the treatment group showed significantly higher learning gains and better scores than students in a comparison group who learned the same material through traditional lectures [32]. Together, these studies indicate that explicit instruction in science process skills helps students to better learn biology content.

Although most scientists know science process skills are central to doing science, there have been very few studies about the acquisition and mastery of science process skills in college level biology courses. Zimmerman [171] provides an excellent overview on the history of scientific reasoning research, beginning with the early work of Siegler [172] through the work of Schauble [173], upon which many current studies are based. The review also highlights a gap between cognitive developmentalists and science educators, implying that an interdisciplinary approach using findings from both fields to enhance student's acquisition of science process skills would be most effective. Lastly, the review describes studies showing the need for understanding how scientific reasoning occurs in a domain-specific manner, including biology. For example, a study by Bowen and Roth show that the development of inscription-related processes (ability to read graphs, data tables, diagrams, etc…) by undergraduates is likely hindered by textbooks because of the ways in which the inscriptions are presented [118].

Domain-specific studies focused to measure how unique treatments impacted student understanding specific content in biology. An example of domain-specific learning is that Lu et al. asked students in two different developmental biology classes to make Play Doh representations of embryos during early development in order to identify their preconceptions. Researchers then used graphical representations to determine if instruction had dispelled the common misconception that embryos increased in volume during early development [128]. Although their findings showed that some students held their misconceptions even after instruction, it prompted the instructors to think deeply about their teaching strategies and when best to implement model-organism courses in the curriculum [128].

Undergraduate Research Experiences: Student Performance or Outcomes

Both E. Seymour and D. Lopatto have conducted interviews or administered surveys to large numbers of students at many U.S. institutions to determine the benefits of research for undergraduates and the progression rate of those students into an advance degrees [136, 138]. In Lopatto's study, 1,135 participants took part in the survey, most of whom declared biology as their area of study. Of those respondents, 83% went on, or intended to go on, to earn advanced degrees [136]. The percentages of underrepresented minorities and Caucasians who intended to earn advanced degrees were similar [136]. This is in contrast to findings from other studies that show the undergraduate research experience significantly influenced the decision of underrepresented minorities to pursue advance degrees [139]. The benefits of undergraduate research have also been documented in other countries. A 15 year study by Santer of the U.K.

showed that students who took a professional training year (PTY; neuroscience research experience) as part of their neuroscience degree performed significantly better in courses and had significantly higher graduating GPAs than students who did not elect to participate in research [137]. Moreover, 1 in 3 PTY students went on to earn Ph.D.s compared to 1 in 11 students who did not participate in the program [137]. Lastly, some studies show that attitudes about science may impact students' success in science regardless of an undergraduate research experience [174].

Improving the Success of Underrepresented Groups

The most effective strategies for improving the success of underrepresented groups in the biological sciences have been seen in supplemental instruction programs that offer these students academic advising, instruction in study skills, access to research experiences and a network of peers in science [19, 139, 141]. An important aspect of these programs is that they target URMs early and help them to overcome academic, financial, and social barriers that often impede their path into science.

Less common are studies that investigate women's success in science. Although women are now earning more undergraduate degrees in biology than men, they do not equal the number of men at the full professor rank in biology departments and many leave science all together due to reported unfavorable climates [175, 176]. Damschen et al. analyzed seven of the most frequently used undergraduate ecology textbooks for representations of women as working scientists and women acknowledged as scientific reviewers, publishers or editors [140]. They found that women were largely underrepresented in textbooks and surveys of students in courses using these texts showed that the students could not provide examples of female scientists in ecology. However, enrichment of the course with biographical sketches or stories of women scientists significantly increased the number of women scientists that female students could remember; male students showed no gains in their recall of women scientists in the enriched course [140]. Further work by this group showed similar results [143].

Category II: Student Attitudes or Beliefs about Learning Biology

Characteristics

BER studies that investigated the interaction between the affective and cognitive domains of student learning make up this category. Three main groups within this category that emerged from the literature are: studies that investigated students' motivation for learning biology, student approaches to learning biology, and student beliefs about biological content, particularly evolution. Studies having control groups, or those that compared groups that received varying treatments, were considered "controlled" studies. Studies were classified as having supporting data if they showed differences in attitudes, beliefs, or motivation either pre- and post-treatment or based on a comparison group. Any study that reported only self-reported gains were scored separately. The percentage of studies having these and other characteristics can be found in Table 2.

Table 2. Characteristics of BER Studies – Category 2

Group % from 2001-10 (N) citations	**Average length of studies in semesters***	**% studies done with only majors**	**% studies done in lower division courses**	**% studies done in a course setting**	**% studies measuring achievement by URM or gender**	**% studies with controls or comparison groups**	**% studies with Supp. data (SR)†**
Attitudes and Beliefs about Learning Biology╪ 80% 2001-2010 (N=20) [70, 174, 177-192]	1.5	45%	80%	75%	5%	25%	60% (95%)

* Studies based on the quarters were treated as semesters for data analysis, albeit most were reported as semesters

† Studies having a positive impact reported learning gains from pre- and post-tests, exam scores, grades, retention, etc…; self reported (SR) gains in knowledge or skills were also considered in this analysis

╪ Student attitudes about active learning strategies were analyzed and reported in that group of category 1.

Data collected in the studies analyzed in this category were qualitative or quantitative depending on the kind of study. Studies about students' beliefs related to learning biology or their attitudes about how they perceive or experience certain phenomena often involved interviews where the interview was transcribed and subsequently analyzed. Information based on interviews or surveys was often converted into quantitative data to indicate the percentage of students who responded in a particular way. In many cases, verbal examples of responses to particular questions were also presented. Less common were other kinds of examples of student work, such as drawings or concept maps. However, when these examples were presented, the authors commonly interpreted the frequency in which a particular outcome occurred and presented those as percentages of responses or a mean value of the respondents.

<u>Descriptions</u>

Motivation for Learning

The role of motivation in learning is complex, which is likely why it has long been an active area of cognitive psychology research. Motivation for learning involves one's beliefs about how learning happens and about knowledge itself – motivation towards knowledge as an object influences knowledge acquisition [193, 194]. Students who have beliefs that knowledge attainment is simple and certain are less likely to use approaches that require higher order cognitive skills and self-construction of knowledge; these students typically want a more structured pathway for obtaining knowledge [70]. Alexander et al. describes that domain (biology, physics, etc…) learning from novice to expert occurs due to simultaneous changes in interest, knowledge, and learning strategies [195, 196]. Therefore, if we are to help students become critical thinkers in science, we need to find effective ways to engage their feelings and values about the subjects we present.

Approaches to Learning

College students' approaches to learning differ substantially depending on their prior experiences, expectations, attitudes toward the topic, previous knowledge, and many other variables. The study strategies that students employ are often related to how they attribute success and failure [197]. In science courses, students may attribute failure to aptitude – an uncontrollable cause – and resist changing their study strategies to improve their performance

[198]. A student's confidence in his or her ability to perform a task may also affect their overall performance [199]. The most successful students are those who can self-regulate their learning by being proactive, setting goals for themselves, adopting strategies to achieve their goals, monitoring their behavior, and being self-reflective about the effectiveness of their strategies [200]. Where and when students develop these skills varies, but if we are to help biology students' performance in our courses we need to identify strategies to teach them these skills.

Student Beliefs about Biological Content and Science

Not only do students come to college with alternative conceptions about the world around them, they also have personal beliefs that can affect their learning. Both misconceptions and engrained belief systems can hinder knowledge acquisition, and therefore need be addressed in the learning process. Until the last decade, research has mainly focused on conceptual change based on the cognitive domain, not the affective domain [188, 201]. However, recent work has begun to investigate how belief identification and one's willingness to question their beliefs affects their conceptual change [201]. Therefore, it is recognized that the learner *decides* to consider alternative views to their closely held beliefs. In the science community, beliefs are often considered subjective and not based on evidence, in so far as scientists disregard the terminology "belief in evolution" and prefer the "acceptance of evolution" [178]. To help students accept scientific theories, such as evolution, instructors need to accept that some students are only willing to change their belief systems under simple and non-threatening conditions.

Theoretical Frameworks

The affective domain is often studied in conjunction with the cognitive domain and has been formally described as part of a system for identifying understanding and addressing how people learn; it is one of three parts making up the *Taxonomy of Educational Objectives: The Classification of Educational Goals* [202]. Most studies in this section describe how the affective domain influences learning of biology. In some cases students' attribute failure on a test or in a course as uncontrollable, often because they associate it with innate ability. Uncontrollable failure may lead to students feeling helplessness, which only exacerbates the problem. In other situations, students feel the need for reward and attend class and engage in learning on the basis of that emotion [186].

Major Findings

Hynd et al. conducted a study of student motivation and learning strategy use with high school physics students who intended to go to college and introductory biology students in college [182]. They hoped a comparison of the two groups would inform them of differences in motivation and strategies employed. They found that students in both groups felt motivated to learn because of grades and relevance of the information to their daily lives; they also found that both groups disregarded social interactions with their peers as motivational. For college students it was noted that they often equated motivation with effort. If they studied and attended class they felt motivated, but a lack of either activity further decreased their motivation. Higher performing students were more aware of the many outside influences that could affect their performance, possibly indicating higher metacognition. However, the at-risk biology students were those who felt debilitated by poor exam scores and had low feelings of self-efficacy and motivation [182]. The findings from this study implicate that instructors should strive to make content relevant to the learner, and give frequent graded in-class and homework assignments to improve engagement. They should also emphasize group work so that students see the value in social interactions with their peers. All of these teaching strategies will likely improve student motivation for learning and ultimately performance.

A series of studies by R. Moore and colleagues investigated student attitudes toward attendance and learning biology as a relationship to their attendance and grades in high school biology courses. They showed that incoming freshman in biology courses believed they would achieve an “A” or “B” in the course, and none indicated they would earn a “D” or “F” [186]. Interestingly, of 1,837 students surveyed, none of these same students earned a “D” or “F” in high school biology [186]. Moreover, the majority of students felt high school prepared them well for college yet, on average, only half the students indicated that "high school challenged me; I had to work hard." The majority of students also claimed they would attend class more if they received points for attendance and would attend less if they didn't. Those students who attended the fewest college biology classes made up the greatest population of students who indicated they would attend class if they received points for attendance; these students were also the least likely to indicate that they believed attending class had been important to their success in high school. Based on an end of the year survey, students who earned Ds and Fs in the course were seven times more likely to indicate that they wished that they had attended class more often compared to students who earned As in the course [186]. Thus, student attitudes about attendance can be surveyed at the beginning of a course to inform instructors of at-risk students and intervene appropriately. Another study from this group provided interview data showing that students liked the option of not attending class every day, had no real incentive to do so because they were not awarded points, and their absences likely went unnoticed in the large lecture format [185]. They also showed, not surprisingly, a strong correlation between attendance and grades. A subsequent study in a laboratory course showed that by showing students data about the relationship between attendance and grades, as well as changing the policy for the number of allowable absences from 3 to 2, significantly decreased the overall absences.

Approaches to Learning

Bowers et al. conducted a study to investigate the relationship between students' confidence in their knowledge of their course material and their grades in the course [203]. In three sections of a biology course having a common syllabus and lecture schedule, they implemented a knowledge survey to determine how students would rank their confidence for answering course content questions pre- and post-instruction. The instrument was designed to have at least 25% of the questions at higher cognitive levels of Bloom's Taxonomy [202]. During the first two weeks of the semester students took the pretest, and in the last two weeks they took the posttest. A comparison of pre- and post-test scores showed that students had significantly increased their confidence, likely due to content acquisition. Further analysis showed that student's pretest confidence scores were not predictive of their ability to answer questions similar to the ones on the knowledge survey or their final grades [203]. These findings suggest that incoming freshman do not accurately judge their incoming knowledge. The results also signify that entering students need help in developing their metacognitive skills.

Student Beliefs about Biological Content and Science

Students may be able to effectively apply knowledge about evolution but still not accept evolution because of their beliefs. Blackwell et al. administered a questionnaire about a subject with which students were familiar – dogs and breeding [178]. The questions required students to comprehend and apply information about evolution and also queried students about their beliefs in evolution. While the majority (93%) of students could effectively apply knowledge about evolution, only 35% considered evolution as the primary basis for the progression of life on earth and only 29% considered evolution compatible with their belief system [178]. These findings are not surprising as a similar study by Sinatra et. al. showed that there was no relationship between a student's knowledge of evolution and reported acceptance of evolution, even when the same students could demonstrate a significant relationship between knowledge and acceptance of photosynthesis [188].

Category III: Studies that Test and Validate Instruments

<u>Characteristics</u>

Biology focused concept inventories and biology-related assessment instruments made up most of the items in this category. However, if instruments designed for general use in science had been employed in the study of biology, they were included in the analysis. Study characteristics for concept inventories and validated instruments included the year in which the tool was developed, the content area for which the tool was made, and whether or not the tool had been tested for reliability and validity. A summary of the items and their general characteristics can be found in Table 3.

Table 3. Characteristics of BER Studies – Category 3

Group **% from 2001-10** **(N)** **Citations**	**Instrument Name** **Validated** √	**Sub-discipline of biology**
Concept Inventories 80% 2001-2010 (N=7) [152-156, 204, 205]	Biology Concept Inventory Biology Concept Framework Conceptual Inventory of Natural Selection (CINS) √ Core Principles of Physiology Genetics Literacy Assessment Instrument √ Genetics Concept Assessment √ Introductory Molecular and Cell Biology Assessment √	General Biology General Biology Evolution Physiology Genetics Genetics Cell and Molecular
Validated Instruments 83% 2001-2010 (N=6) [191, 203, 206-209]	Views About Sciences Survey: VASS√ Revised Two-Factor Study Process Questionaire √ Survey of Undergraduate Research Experiences √ Knowledge Survey Student-Achievement and Process-Skills Instrument √ Rubric for Science Writing √	General Science General Science General Science General Science General Science General Science

<u>Descriptions</u>

Concept Inventories

Concept inventories (CI) are tests that are designed to assess students' preconceptions and measure conceptual understanding or change given a particular treatment. The tests are in a multiple-choice format, have strong distractors based on common student misconceptions about the content, and are typically employed in introductory courses [1, 3]. Development of a CI requires a broad range of expertise and extensive testing to validate that the questions test the specific target content and that the test is reliable over a wide range of students coming from different backgrounds and levels of preparation. CIs are relatively new in the biological sciences with all having been developed in the past 8 years. There is only one general biology concept inventory, but it is not widely used in the classroom [205]. General biology CIs are difficult to produce because faculty must agree on the core concepts that should be included. Given the numerous sub-disciplines in biology, there is a great need for many more of these diagnostics to be made for specific content areas.

Other Assessment Instruments

Validated instruments to measure student learning, attitudes, or experiences in biology are valuable for designing curricula to help students become scientifically competent and progress towards mastery. In this search, there were many instruments that were designed for general use in science but have been (or could be) employed by biology education researchers because no other tool exists.

Theoretical Frameworks

While very few studies indicated the theoretical framework in which they were situated, research in this section aimed to develop tools that would better identify and measure students' misconceptions about biology concepts or their attitudes about science when learning biology. Students are not an empty slate when they enter the classroom and come with a subset of preconceptions about topics in biology. Concept inventories typically measure the prevalence and persistence of wrong preconceptions, or misconceptions, among biology students. Effective instruction can help students address and overcome their misconceptions; concept inventories are the tools by which biology instructors can measure students' conceptual change. The importance of this is best stated by D. Ausubel [210]: "*If I had to reduce all of educational psychology to just one principle, I would say this; the most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly.*"

Major Findings

Concept Inventories

The first step in creating a CI is to find agreement among faculty as to what the core concepts are in a particular area. The core concepts in any discipline can serve as a foundation for the diagnosing students understanding of the topic and teaching strategies to make sure the core concepts are effectively learned. Michael et al. convened a group of physiology faculty at the Conceptual Assessment Biology meeting to address two questions: 1) what students should learn in physiology and 2) how will we know if they have learned it [154]? This illustrates how professional meetings or other venues can help faculty come together and identify the core concepts of any sub-discipline of biology.

One of the earliest developed and most widely adopted CIs in biology is the Concept Inventory of Natural Selection (CINS) [152]. The 20-item, multiple choice test is based on real scientific studies and uses common alternative conceptions as distractors – the distractors were identified through interviews with several students. The test was originally administered with nonmajors and majors in biology and followed up with interviews with the students to confirm the results. Subsequently the test was validated, tested for reliability, and distributed through publication [152]. There have been no reports of revisions since the publication in 2002.

The Genetics Concept Inventory is a very recent, but well established, CI for use in non-major and major biology courses [156]. The 25-question test was validated and found to be reliable through field-tests with over 600 biology students. The CI was further tested, and the authors showed positive correlation between learning gains on the CI and exam scores [156]. In other studies, this CI was employed to investigate the differences between majors and non-majors' understanding of genetics and their approaches to learning [183]. Their findings showed a difference in learning gains between the two groups; other surveys of the same students also showed differences in motivation and approaches to learning genetics. This work best illustrates how CIs can be used to effectively monitor student understanding and relate it to variables that affect learning.

Other Assessment Instruments

The following are examples of validated tools that have been adopted by the biology education research community: 1) The Revised Two Factor Study Process Questionnaire (R-SPQ-2F) is a newer version of a test to evaluate student's approaches to learning in a manner reflective of contemporary teaching [206]. Although this instrument was redesigned by J. Biggs for general purpose, it is the only instrument that measures deep vs surface approaches to student learning and could be valuable in the design of similar instruments for biology. 2) The Views about Science Survey (VASS), developed by Halloun and Hestenes, was also designed for general use in the sciences to assess students' attitudes about science [191]. 3) The Survey of Undergraduate Research Experiences (SURE) is a survey aimed to measure self-reported data about science students' perceptions on the benefits of undergraduate research [209]. Collectively, these tools are great resources for educators who wish to assess a wide range of student attributes related to their college experience. More refined tools for use specifically in biology are warranted.

IV. Limitations in the current research and future directions

An extensive search of BER studies revealed many exciting and relatively new areas of research in three main areas: student learning and performance, student attitudes and belief, and concept inventories and assessment tools in biology. BER is beginning to have momentum, which was seen in the marked increase in the number of publications during the past decade. The BER community is active in many sub-disciplines of biology and many studies were structured with control or comparison groups. Nonetheless, the field is primarily conducting quasi-experimental research, lacking complete randomization of their subjects, which is not an easy task to accomplish in an educational setting. Most studies were done over a relatively short time frame (1-2 semesters) and did not account for differences in student populations.

Analysis of numerous studies included in this study showed several other limitations in the work presented. Most of the studies in all categories were conducted with only majors in a course setting. There are very few studies done with upper-division students or those that were done at multiple institutions. Given the amount of data in support of active learning, it is also surprising that there were not a greater number of studies that aimed to measure student performance based on the same treatment, but implemented at multiple institutions. As a result, it is somewhat difficult to conclude that the same teaching strategy would produce similar results outside of the class setting or department in which it was tested. Therefore, it is less likely that others would readily adopt any particular strategy – this is highlighted by the fact that some studies seem to “reinvent the wheel”, creating their own questions or assessment tools for measuring essentially the same thing that had assessed at another institution. There is a real need for mechanisms, such as one large meeting, where biology education researchers can meet and form collaborations for such endeavors.

Another major limitation in the studies analyzed was that many studies used self-made, non-validated instruments for measuring student learning or attitudes. This is a substantial problem if we are to confirm the data and compare it to others work. It also indicates that the BER community needs many more validated tests that can be shared broadly. One suggestion would be training workshops at professional meetings or descriptive articles in popular journals outlining the process for creating valid and reliable instruments.

Many of the studies did not measure student learning or attitudes based on student backgrounds. While many reported a positive impact after implementing a teaching strategy or providing students with an experience, they frequently did not measure the outcomes of underrepresented groups or by gender. Without collecting these kinds of data it should not be assumed that any new teaching strategy would be effective for these groups as well. For most studies it is difficult to determine if underrepresented groups benefit as much from the intervention as the entire class did.

There are many gaps in BER, particularly in areas investigating the affective domains of student learning in biology. There were several studies that measured how students felt about a particular teaching strategy, but only a few that sought to better understand how student attitudes and beliefs affect their approaches to learning of biology. Another important area that has not been well investigated is student metacognition and their ability to develop these skills while learning biology. Given that metacognition is such a critical component of effective learning, it warrants further attention. There is a great deal of previous research from which biology education researchers can pull from when designing studies and curriculum to help students develop this important skill.

How students learn biology in an interdisciplinary manner was another area of research that was very poorly represented. Indeed, from the search emerged only one publication on the subject and that was in a laboratory setting. Moreover, there were no studies comparing how the process of learning biology is different to learning in other STEM disciplines. Given the extensive vocabulary and skill sets required to study biology, it is an important area of research to pursue.

Studies aimed at measuring students' acquisition and mastery of science process skills, such as graphing, data analysis, experimental design, and oral communication received poor attention as well. Given that science process skills are central to doing biology, it is imperative that we explore how students learn these skills and in what kinds of environments they learn skills best. This is one area for which new, validated instruments could be developed – assessment tools that could be used broadly in the sub-disciplines of biology.

There are a wide variety of studies occurring in BER, and given the disparate sub-disciplines of biology the field has unique challenges compared to other DBER groups. Nonetheless, BER is off to a great start – improving student learning of biology at a rapid pace.

Appendix A. Complete list of the sources used in this study

Source	**Number of Cases**	**Years Published**
Academic Medicine	2	1993-2006
Active Learning in Higher Education	2	2005-2007
Advances in Physiology Education	13	1996-2009
American Biology Teacher	6	1988-2008
American Journal of Pharmaceutical Education	1	2007
Annual Review of Cell and Developmental Biology	1	2009
Assessment and Evaluation in Higher Education	4	1997-2010
Australasian Journal of Educational Technology	1	2005
Biochemistry and Molecular Biology Education	8	2001-2009
Bioscene: Journal of College Biology Teaching	6	2003-2006
BioScience	6	1991-2008
Bioscience Education	9	2004-2010
British Journal of Educational Psychology	2	2000-2001
Cell Biology Education/CBE-Life Sciences Education	50	2002-2010
Computers and Education	1	1994
Contributions to Human Development	1	1990
Council on Undergraduate Research Quarterly	1	2003
Developmental Psychology	1	1984
Developmental Review	1	2000
Electronic Journal of Science Education	1	2005
First International Conference on Concept Mapping	1	2004
Frontiers in Ecology and the Environment	1	2005
Genetics	1	2008
Higher Education Research and Development	1	2007
Innovations in Education and Teaching International	1	2004
Innovative Higher Education	1	2009
International Journal for the Scholarship of Teaching and Learning	1	2009
International Journal of Science Education	5	1999-2009
Journal of Academic Librarianship	1	2005
Journal of Biological Education	2	2001-2003
Journal of Chemical Education	2	2002-2005
Journal of College Reading and Learning	1	2003
Journal of College Science Teaching	12	1994-2010
Journal of Educational Psychology	1	2000
Journal of Environmental Education	1	1998
Journal of Food Science Education	1	2005
Journal of Higher Education	1	2010
Journal of Microbiology and Biology Education	1	2009
Journal of Personality and Social Psychology	1	1995
Journal of Research in Science Teaching	15	1977-2008
Journal of Research on Computing in Education	1	2001
Journal of Science Education and Technology	2	2002

Journal of Science Teacher Education	1	2010
Journal of the Scholarship of Teaching and Learning	1	2008
Journal of Undergraduate Neuroscience Education	1	2010
Journal of Verbal Learning and Verbal Behavior	1	1977
Learning and Instruction	2	1994-1995
Medical Teacher	1	1992
Microbiology Education	4	2000-2003
Psychology of Women Quarterly	1	2007
Psychology Reviews	1	1977
Reading and Writing Quarterly: Overcoming Learning Difficulties	1	2000
Reading Psychology	1	2001
Research in Science Education	2	2002-2008
Review of Educational Research	2	1990-1999
Science	3	2005-2010
Science Education	1	2007
Science Educator	1	2008
TechTrends: Linking Research and Practice to Improve Learning.	1	2009
The Learning Assistance Review	1	2007
Theory into Practice	1	2002
Books or Book Sections	16	1916-1999
Conference Proceedings	9	1988-2004
Reports	4	1986-2008
Webpage	1	2008

References

1. D'Avanzo, C., *Biology Concept Inventories: Overview, Status, and Next Steps.* BioScience., 2008. **39**(11): p. 952-978.
2. Wood, W.B., *Innovations in teaching undergraduate biology and why we need them.* Annual Review of Cell and Developmental Biology, 2009**25**: p. 93-112.
3. Libarkin, J., *Concept Inventories in Higher Education Science*, in *A manuscript prepared for the National Research Council Promising Practices in Undergraduate STEM Education Workshop 2*. 2008: Washington, D.C.
4. Schroeder, C.M., et al., *A Meta-Analysis of National Research: Effects of Teaching Strategies on Student Achievement in Science in the United States.* Journal of Research in Science Teaching., 2007.
5. Daempfle, P.A., *Instructional Approaches for the Improvement of Reasoning in Introductory College Biology Courses: A Review of the Research*. 2002.
6. Anderson, W.L., S.M. Mitchell, and M.P. Osgood, *Comparison of Student Performance in Cooperative Learning and Traditional Lecture-Based Biochemistry Classes.* Biochemistry and Molecular Biology Education., 2005.
7. Armbruster, P., et al., *Active Learning and Student-Centered Pedagogy Improve Student Attitudes and Performance in Introductory Biology*. CBE - Life Sciences Education., 2009.
8. Armstrong, N., S.-M. Chang, and M. Brickman, *Cooperative Learning in Industrial-Sized Biology Classes.* CBE - Life Sciences Education., 2007.
9. Born, W.K., W. Revelle, and L.H. Pinto, *Improving Biology Performance with Workshop Groups.* Journal of Science Education and Technology., 2002.
10. Burrowes, P.A., *A Student-Centered Approach to Teaching General Biology That Really Works: Lord's Constructivist Model Put to a Test.* American Biology Teacher., 2003.
11. Butler, J.A., *Use of Teaching Methods within the Lecture Format.* Medical Teacher., 1992.
12. Buxeda, R.J. and D.A. Moore, *Transforming a sequence of microbiology courses using student profile data.* Microbiology Education, 2000. **1**(1): p. 1-6.
13. Caldwell, J.E., *Clickers in the Large Classroom: Current Research and Best-Practice Tips.* CBE - Life Sciences Education., 2007.
14. Casem, M.L., *Active Learning Is Not Enough.* Journal of College Science Teaching., 2006.
15. Christianson, R.G. and K.M. Fisher, *Comparison of Student Learning about Diffusion and Osmosis in Constructivist and Traditional Classrooms.* International Journal of Science Education., 1999.
16. Cliff, W.H. and A.W. Wright, *Directed case study method for teaching anatomy and physiology*. Advances in Physiology Education, 1996.**15**(1): p. 19-28.
17. Cortright, R.N., H.L. Collins, and S.E. DiCarlo, *Peer Instruction Enhanced Meaningful Learning: Ability to Solve Novel Problems.* Advances in Physiology Education., 2005.
18. Cortright, R.N., et al., *Student retention of course content is improved by collaborative-group testing.* Advances in Physiology Education, 2003.**27**: p. 102-108.
19. Dirks, C. and M. Cunningham, *Enhancing Diversity in Science: Is Teaching Science Process Skills the Answer?* CBE - Life Sciences Education., 2006. **5**(3): p. 218-226.
20. Ebert-May, D., C. Brewer, and S. Allred, *Innovation in Large Lectures--Teaching for Active Learning.* BioScience., 1997.

21. Fonseca, A., C.I. Extremina, and A. Freitas da Fonseca. *Concept Mapping: A Strategy for Meaningful Learning in Medical Microbiology*. in *First International Conference on Concept Mapping*. 2004. Pamplona Spain.
22. Francom, G., et al., *Biology 100: A Task-Centered, Peer-Interactive Redesign.* TechTrends: Linking Research and Practice to Improve Learning., 2009.
23. Freeman, S., et al., *Prescribed Active Learning Increases Performance in Introductory Biology*. CBE - Life Sciences Education., 2007.
24. Gehring, K.M. and D.A. Eastman, *Information Fluency for Undergraduate Biology Majors: Applications of Inquiry-based Learning in a Developmental Biology Course.* CBE - Life Sciences Education., 2008.
25. Goodwin, L., J.E. Miller, and R.D. Cheetham, *Teaching Freshman to Think: Does Active Learning Work?* BioScience., 1991. **41**(10): p. 719-722.
26. Harris, M.A., et al., *A Combination of Hand-Held Models and Computer Imaging Programs Helps Students Answer Oral Questions about Molecular Structure and Function: A Controlled Investigation of Student Learning.* CBE - Life Sciences Education., 2009.
27. Hoffman, E.A., *Successful Application of Active Learning Techniques to Introductory Microbiology*. Microbiology Education, 2001. **2**(1): p. 5-11.
28. Hoffman, K., et al., *Problem-Based Learning Outcomes: Ten Years of Experience at the University of Missouri-Columbia School of Medicine.* Academic Medicine, 2006. **81**(7): p. 617-625.
29. Hufford, T.L., *Increasing Academic Performance in an Introductory Biology Course.* BioScience., 1991.
30. Huxham, M., *Learning in Lectures: Do 'Interactive Windows' Help?* Active Learning in Higher Education., 2005.
31. Johnson, M.A. and A.E. Lawson, *What Are the Relative Effects of Reasoning Ability and Prior Knowledge on Biology Achievement in Expository and Inquiry Classes?* Journal of Research in Science Teaching., 1998.
32. Kitchen, E., et al., *Teaching Cell Biology in the Large-Enrollment Classroom: Methods to Promote Analytical Thinking and Assessment of Their Effectiveness.* Cell Biology Education., 2003.
33. Klappa, P., *Promoting Active Learning through "Pub Quizzes"--A Case Study at the University of Kent.* Bioscience Education., 2009.
34. Klionsky, D.J., *Constructing Knowledge in the Lecture Hall.* Journal of College Science Teaching., 2002.
35. Knight, J.K. and W.B. Wood, *Teaching More by Lecturing Less.* Cell Biology Education., 2005.
36. Lawson, A., et al., *Evaluating College Science and Mathematics Instruction: A Reform Effort That Improves Teaching Skills.* Journal of College Science Teaching., 2002.
37. Lord, T.R. *Is the Final Grade in College Biology a True Measure of Student Knowledge?* 1988.
38. Marbach-Ad, G. and P.G. Sokolove, *Can Undergraduate Biology Students Learn To Ask Higher Level Questions?* Journal of Research in Science Teaching., 2000.
39. Marbach-Ad, G. and P.G. Sokolove, *The Use of E-Mail and In-Class Writing To Facilitate Student-Instructor Interaction in Large-Enrollment Traditional and Active Learning Classes.* Journal of Science Education and Technology., 2002.

40. Marrs, K.A. and G.W. Chism, III, *Just-in-Time Teaching for Food Science: Creating an Active Learner Classroom.* Journal of Food Science Education., 2005.
41. McDaniel, C.N., et al., *Increased Learning Observed in Redesigned Introductory Biology Course that Employed Web-Enhanced, Interactive Pedagogy*. CBE - Life Sciences Education., 2007.
42. McInerney, M.J. and L.D. Fink, *Team-Based learning enhances long-term retention and critical thinking in an undergraduate microbial physiology course* Microbiology Education, 2003. **4**: p. 3-12.
43. Montelone, B.A., D.A. Rintoul, and L.G. Williams, *Assessment of the Effectiveness of the Studio Format in Introductory Undergraduate Biology*. CBE - Life Sciences Education., 2008.
44. Nehm, R. and L. Reilly, *Biology majors' knowledge and misconceptions of natural selection.* BioScience., 2007. **57**(3): p. 263-272.
45. Nelson, J., et al., *Cloning the Professor, an Alternative to Ineffective Teaching in a Large Course.* CBE - Life Sciences Education., 2009.
46. Orsmond, P., S. Merry, and A. Callaghan, *Implementation of a Formative Assessment Model Incorporating Peer and Self-Assessment.* Innovations in Education and Teaching International., 2004.
47. Orsmond, P., S. Merry, and K. Reiling, *A Study in Self-Assessment: Tutor and Students' Perceptions of Performance Criteria.* Assessment and Evaluation in Higher Education., 1997.
48. Orsmond, P., S. Merry, and K. Reiling, *The Use of Student Derived Marking Criteria in Peer and Self-Assessment.* Assessment and Evaluation in Higher Education., 2000.
49. Paschal, C.B., *Formative assessment in physiology teaching using a wire- less classroom communication system.* Advances in Physiology Education, 2002. **26**: p. 299-308.
50. Pelaez, N., *Problem-based writing with peer review improves academic performance in physiology*. Advances in Physiology Education, 2002. **26**: p. 174-184.
51. Perez, K.E., et al., *Does Displaying the Class Results Affect Student Discussion during Peer Instruction?* CBE - Life Sciences Education., 2010.
52. Peters, A., *Teaching biochemistry at a minority-serving institution: An evaluation of the role of collaborative learning as a tool for science mastery*. Journal of Chemical Education, 2005. **82**(4): p. 571-574.
53. Pisani, A.M. *Involvement through Cooperative Learning: An Attempt To Increase Persistence in the Biological Sciences. ASHE Annual Meeting Paper*. 1994.
54. Preszler, R.W., *Cooperative Concept Mapping: Improving Performance in Undergraduate Biology*. Journal of College Science Teaching, 2004. **33**(6): p. 30-35.
55. Preszler, R.W., *Student and teacher learning in a supplemental learning biology course.* Bioscene: Journal of College Biology Teaching., 2006. **32**(2): p. 21-25.
56. Preszler, R.W., *Replacing Lecture with Peer-Led Workshops Improves Student Learning.* CBE - Life Sciences Education., 2009.
57. Preszler, R.W., et al., *Assessment of the Effects of Student Response Systems on Student Learning and Attitudes over a Broad Range of Biology Courses.* CBE - Life Sciences Education., 2007. **6**(1): p. 29-41.
58. Rao, S.P., H.L. Collins, and S.E. DiCarlo, *Collaborative testing enhances student learning.* Advances in Physiology Education, 2002. **26**: p. 37-41.

59. Roy, H., *Studio vs. Interactive Lecture Demonstration--Effects on Student Learning.* Bioscene: Journal of College Biology Teaching., 2003. **29**(1): p. 3-6.
60. Rybarczyk, B.J., et al., *A Case-based approach increases student learning outcomes and comprehension of cellular respiration concepts.* Biochemistry and Molecular Biology Education., 2007. **35**(3): p. 181-186.
61. Smith, M.K., et al., *Why peer discussion improves student performance on in-class concept questions.* Science, 2009. **323**(5910): p. 122-4.
62. Steele, J., *Effect of essay-style lectures quizzes on student performance on anatomy and physiology exams.* Bioscene: Journal of College Biology Teaching., 2003. **29**(4): p. 15-20.
63. Tessier, J., *Using peer teaching to promote learning in biology*. Journal of College Science Teaching, 2004. **33**(6): p. 16-19.
64. Tessier, J., *Small-group peer teaching in an introductory biology classroom.* Journal of College Science Teaching, 2007. **36**(4): p. 64-69.
65. Traver, H.A., et al., *Student Reactions and Learning: Evaluation of a Biochemistry Course That Uses Web Technology and Student Collaboration.* Biochemistry and Molecular Biology Education., 2001.
66. Trempey, J.E., M.M. Skinner, and W.A. Siebold, *Learning microbiology through cooperation: Designing cooperative learning activities that promote interdependence, interaction, and accountability*. Microbiology Education, 2002. **3**(1): p. 26-36.
67. Udovic, D., et al., *Workshop Biology: Demonstrating the Effectiveness of Active Learning in an Introductory Biology Course.* Bioscience., 2002.
68. Walker, J.D., et al., *A Delicate Balance: Integrating Active Learning into a Large Lecture Course.* CBE - Life Sciences Education., 2008.
69. Wilke, R.R., *The effect of active learning on student characteristics in a human physiology course for nonmajors.* Advances in Physiology Education, 2003. **27**: p. 207-223.
70. Windschitl, M. *Student Epistemological Beliefs and Conceptual Change Activities: How Do Pair Members Affect Each Other?* 1997.
71. Wright, R., *Learning cell biology as a team: A project-based approach to upper-division cell biology*. Cell Biology Education, 2002. **1**: p. 145-153.
72. Yarden, H., G. Marbach-Ad, and J.M. Gershoni, *Using the Concept Map Technique in Teaching Introductory Cell Biology to College Freshmen.* Bioscene: Journal of College Biology Teaching., 2004.
73. Brauner, A., et al., *Open-Ended Assignments and Student Responsibility*. Biochemistry and Molecular Biology Education., 2007.
74. Brickman, P., Gormally, C., Armstrong, N. and Hallar, B., *Effects of Inquiry-based Learning on Students' Science Literacy Skills and Confidence.* International Journal for the Scholarship of Teaching and Learning, 2009. **3**(2).
75. Burrowes, P. and G. Nazario, *Promoting Student Learning through the Integration of Lab and Lecture: The Seamless Biology Curriculum.* Journal of College Science Teaching., 2008.
76. Casem, M.L., *Student Perspectives on Curricular Change: Lessons from an Undergraduate Lower-Division Biology Core.* CBE - Life Sciences Education., 2006.
77. Halme, D.G., et al., *A Small-Scale Concept-Based Laboratory Component: The Best of Both Worlds.* CBE - Life Sciences Education., 2006.

78. Lord, T. and T. Orkwiszewski, *Moving from Didactic to Inquiry-Based Instruction in a Science Laboratory*. American Biology Teacher., 2006.
79. Metz, A.M., *Teaching Statistics in Biology: Using Inquiry-Based Learning to Strengthen Understanding of Statistical Analysis in Biology Laboratory Courses.* CBE - Life Sciences Education., 2008.
80. Myka, J.L. and C.D. Raubenheimer, *Action Research Implemented to Improve Zoology Laboratory Activities in a Freshman Biology Majors Course.* Electronic Journal of Science Education, 2005. **9**(4).
81. Quinn, J.G., et al., *Computer-Based Learning Packages Have a Role, but Care Needs to Be Given as to When They Are Delivered.* Bioscience Education., 2009.
82. Rissing, S.W. and J.G. Cogan, *Can an Inquiry Approach Improve College Student Learning in a Teaching Laboratory?* CBE - Life Sciences Education., 2009.
83. Rutledge, M.L., P.M. Mathis, and R.L. Seipelt, *Making Quantitative Genetics Relevant: Effectiveness of a Laboratory Investigation that Links Scientific Research, Commercial Applications, and Legal Issues.* Bioscene: Journal of College Biology Teaching., 2005.
84. Seifert, K., et al., *An Investigative, Cooperative Learning Approach to the General Microbiology Laboratory*. CBE - Life Sciences Education., 2009.
85. Shaffer, C.D., et al., *The Genomics Education Partnership: Successful Integration of Research into Laboratory Classes at a Diverse Group of Undergraduate Institutions.* CBE - Life Sciences Education., 2010.
86. Simmons, M.E., et al., *Assessing the Influence of Field- and GIS-Based Inquiry on Student Attitude and Conceptual Knowledge in an Undergraduate Ecology Lab.* CBE - Life Sciences Education., 2008.
87. Van Hecke, G.R., et al., *An Integration of Chemistry, Biology, and Physics: The Interdisciplinary Laboratory*. Journal of Chemical Education., 2002.
88. Henly, D.C. and A.E. Reid, *Use of the Web To Provide Learning Support for a Large Metabolism and Nutrition Class.* Biochemistry and Molecular Biology Education., 2001.
89. Peat, M., et al., *Revisiting the Impact of Formative Assessment Opportunities on Student Learning.* Australasian Journal of Educational Technology., 2005.
90. Rath, K.A., et al., *Supplemental Instruction in Introductory Biology I: Enhancing the Performance and Retention of Underrepresented Minority Students.* CBE - Life Sciences Education., 2007. **6**(3): p. 203-216.
91. Sanders, D.W. and A.I. Morrison-Shetlar, *Student Attitudes toward Web-Enhanced Instruction in an Introductory Biology Course.* Journal of Research on Computing in Education., 2001.
92. Simpson, M.L. and L. Rush, *College Students' Beliefs, Strategy Employment, Transfer, and Academic Performance: An Examination across Three Academic Disciplines.* Journal of College Reading and Learning., 2003.
93. Wischusen, S.M. and E.W. Wischusen, *Biology Intensive Orientation for Students (BIOS): A Biology "Boot Camp".* CBE - Life Sciences Education., 2007.
94. Aguiar, C., A.A. Carvalho, and C.J. Carvalho, *Use of Short Podcasts to Reinforce Learning Outcomes in Biology*. Biochemistry and Molecular Biology Education., 2009.
95. Azzawi, M. and M.M. Dawson, *The Effectiveness of Lecture-Integrated, Web-Supported Case Studies in Large Group Teaching.* Bioscience Education., 2007.
96. Baggott, G.K. and R.C. Rayne, *The Use of Computer-Based Assessments in a Field Biology Module.* Bioscience Education., 2007.

97. Chen, H.-L. and G. Choi, *Construction of a Digital Video Library: A Socio-Technical Pilot Study on College Students' Attitudes.* Journal of Academic Librarianship., 2005.
98. Collins, M., *Comparing Web, Correspondence and Lecture Versions of a Second-Year Non-Major Biology Course.* British Journal of Educational Technology., 2000.
99. Goldberg, H.R. and G.M. McKhann, *Student test scores are improved in a virtual learning environment.* Advances in Physiology Education, 2000. **23**: p. 59-66.
100. Gossman, P., et al., *Integrating Web-Delivered Problem-Based Learning Scenarios to the Curriculum.* Active Learning in Higher Education., 2007.
101. Gunersel, A.B., et al., *Effectiveness of Calibrated Peer Review[TM] for Improving Writing and Critical Thinking Skills in Biology Undergraduate Students.* Journal of the Scholarship of Teaching and Learning., 2008.
102. Hutchings, G.A. and et al., *Experiences with Hypermedia in Undergraduate Education.* Computers and Education., 1994.
103. Lunsford, E. and K. Bolton, *Coming to Terms with the Online Instructional Revolution: A Success Story Revealed through Action Research.* Bioscene: Journal of College Biology Teaching., 2006.
104. McFarlin, B.K., *Hybrid Lecture-Online Format Increases Student Grades in an Undergraduate Exercise Physiology Course at a Large Urban University.* Advances in Physiology Education., 2008.
105. Merry, S. and P. Orsmond, *Students' Attitudes to and Usage of Academic Feedback Provided via Audio Files.* Bioscience Education., 2008.
106. O'Day, D.H., *The Value of Animations in Biology Teaching: A Study of Long-Term Memory Retention.* CBE - Life Sciences Education., 2007. **6**(3): p. 217-223.
107. Porter, S.G., et al., *Exploring DNA Structure with Cn3D.* CBE - Life Sciences Education., 2007.
108. Toth, E.E., B.L. Morrow, and L.R. Ludvico, *Designing Blended Inquiry Learning in a Laboratory Context: A Study of Incorporating Hands-On and Virtual Laboratories.* Innovative Higher Education., 2009.
109. Garvin-Doxas, K. and M.W. Klymkowsky, *Understanding Randomness and Its Impact on Student Learning: Lessons Learned from Building the Biology Concept Inventory (BCI).* CBE - Life Sciences Education., 2008.
110. Kuech, R., et al. *Technology Rich Biology Labs: Effects of Misconceptions*. 2003.
111. McCrindle, A.R. and C.A. Christensen, *The Impact of Learning Journals on Metacognitive and Cognitive Processes and Learning Performance.* Learning and Instruction., 1995.
112. Michael, J.A., *Students' Misconceptions about Perceived Physiological Responses.* Advances in Physiology Education., 1998.
113. Pelaez, N.J., et al., *Prevalence of Blood Circulation Misconceptions among Prospective Elementary Teachers.* Advances in Physiology Education., 2005.
114. Wilson, C.D., et al., *Assessing Students' Ability to Trace Matter in Dynamic Systems in Cell Biology*. CBE - Life Sciences Education., 2006.
115. Zion, M., T. Michalsky, and Z.R. Mevarech, *The Effects of Metacognitive Instruction Embedded within an Asynchronous Learning Network on Scientific Inquiry Skills. Research Report.* International Journal of Science Education., 2005.
116. Meir, E., et al., *How Effective Are Simulated Molecular-level Experiments for Teaching Diffusion and Osmosis?* Cell Biology Education, 2005. **4**: p. 235-248.

117. Armstrong, N.A., C.S. Wallace, and S.-M. Chang, *Learning from Writing in College Biology*. Research in Science Education., 2008.
118. Bowen, G.M. and W.-M. Roth, *Why Students May Not Learn To Interpret Scientific Inscriptions.* Research in Science Education., 2002.
119. Coil, D., et al., *Teaching the Process of Science: Faculty Perceptions and an Effective Methodology*. CBE - Life Sciences Education., 2010. **9**(4).
120. Ellis, R.A., C.E. Taylor, and H. Drury, *Learning Science through Writing: Associations with Prior Conceptions of Writing and Perceptions of a Writing Program.* Higher Education Research and Development., 2007.
121. Kozeracki, C.A., et al., *An Intensive Primary-Literature-based Teaching Program Directly Benefits Undergraduate Science Majors and Facilitates Their Transition to Doctoral Programs.* CBE - Life Sciences Education., 2006. **5**(4): p. 340-347.
122. Lynd-Balta, E., *Using Literature and Innovative Assessments to Ignite Interest and Cultivate Critical Thinking Skills in an Undergraduate Neuroscience Course.* CBE - Life Sciences Education., 2006.
123. Panizzon, D.L. and A.J. Boulton, *Strategies for Enhancing the Learning of Ecological Research Methods and Statistics by Tertiary Environmental Science Students.* Bioscience Education., 2004.
124. Scott, J., *Students' Perceptions of Skills Acquisition in the Undergraduate Bioscience Curriculum.* Bioscience Education., 2005.
125. Stafford, R., A.E. Goodenough, and M.S. Davies, *Assessing the Effectiveness of a Computer Simulation for Teaching Ecological Experimental Design.* Bioscience Education., 2010.
126. White, T., et al., *The Use of Interrupted Case Studies to Enhance Critical Thinking Skills in Biology*. Journal of Microbiology and Biology Education, 2009. **10**: p. 25-31.
127. Yeoman, K.H. and B. Zamorski, *Investigating the Impact on Skill Development of an Undergraduate Scientific Research Skills Course.* Bioscience Education., 2008.
128. Lu, F.-M., et al., *Student Learning of Early Embryonic Development via the Utilization of Research Resources from the Nematode Caenorhabditis elegans.* CBE - Life Sciences Education., 2008. **7**: p. 64-73.
129. Ocorr, K. and M.P. Osgood, *Self or Help? A Comparison of a Personalized System of Instruction Biochemistry Class to Standard Lecture-Based Biochemistry Class.* Biochemistry and Molecular Biology Education., 2003.
130. Quinn, F., J. Pegg, and D. Panizzon, *First-Year Biology Students' Understandings of Meiosis: An Investigation Using a Structural Theoretical Framework.* International Journal of Science Education., 2009.
131. Shuster, M. and K. Peterson, *Development, Implementation, and Assessment of a Lecture Course on Cancer for Undergraduates.* CBE - Life Sciences Education., 2009.
132. Balster, N., et al., *Entering research: A course that creates community and structure for beginning undergraduate researchers in the STEM disciplines.* CBE - Life Sciences Education., 2010. **9**(2): p. 108-18.
133. Jones, M.T., A.E.L. Barlow, and M. Villarejo, *Importance of Undergraduate Research for Minority Persistence and Achievement in Biology*. Journal of Higher Education., 2010.

134. Kardash, C.M., *Evaluation of an Undergraduate Research Experience: Perceptions of Undergraduate Interns and Their Faculty Mentors.* Journal of Educational Psychology., 2000.
135. Lopatto, D., *The Essential Features of Undergraduate Research.* Council on Undergraduate Research Quarterly, 2003: p. 139-142.
136. Lopatto, D., *Undergraduate Research Experiences Support Science Career Decisions and Active Learning.* CBE - Life Sciences Education., 2007.
137. Santer, R.M., *Benefits of a Professional Training Year for Undergraduates on a Neuroscience Degree Scheme.* Journal of Undergraduate Neuroscience Education, 2010. **9**(1): p. A1-A4.
138. Seymour, E., et al., *Establishing the Benefits of Research Experiences for Undergraduates in the Sciences: First Findings from a Three-Year Study.* Science Education., 2007.
139. Barlow, A.E.L. and M. Villarejo, *Making a Difference for Minorities: Evaluation of an Educational Enrichment Program.* Journal of Research in Science Teaching., 2004.
140. Damschen, E.I., et al., *Visibility Matters: Increasing Knowledge of Women's Contributions to Ecology.* Frontiers in Ecology and the Environment, 2005. **3**(4): p. 212-219.
141. Matsui, J., R. Liu, and C.M. Kane, *Evaluating a Science Diversity Program at UC Berkeley: More Questions than Answers.* Cell Biology Education., 2003.
142. Villarejo, M., et al., *Encouraging Minority Undergraduates to Choose Science Careers: Career Paths Survey Results.* CBE - Life Sciences Education., 2008.
143. Wyer, M., et al., *No Quick Fixes: Adding Content about Women to Ecology Course Materials.* Psychology of Women Quarterly., 2007.
144. Michael, J., *Where's the evidence that active learning works?* Advances in Physiology Education, 2006. **30**: p. 159-167.
145. Johnson, D.W., R. Johnson, and E. Holubec, *Circles of Learning: Cooperation in the Classroom.* 1990, Edina, MN: Interaction Book Company.
146. Osborne, J., *Arguing to learn in science: the role of collaborative, critical discourse.* Science, 2010. **328**(5977): p. 463-6.
147. Springer, L., M.E. Stanne, and S.S. Donovan, *Effects of Small-Group Learning on Undergraduates in Science, Mathematics, Engineering, and Technology: A Meta-Analysis.* Review of Educational Research, 1999. **69**(1): p. 21-51.
148. Johnson, D.W., R. Johnson, and K. Smith, *Active Learning: Cooperation in the College Classroom.* 2nd ed. 1998, Edina, MN: Interaction Book Co.
149. Albanese, M.A. and S. Mitchell, *Problem-based learning: A review of literature on its outcomes and implementation issues.* Academic Medicine, 1993. **68**: p. 52-81.
150. Bransford, J.D., A.L. Brown, and C. R.R., *How People Learn: Brain, Mind, Experience, and School.* 1999, Washington, D.C.: National Research Council (National Academies Press).
151. Chi, M.T.H., J.D. Slotta, and N. deLeeuw, *From things to processes: a theory of conceptual change for learning science concepts.* Learning and Instruction., 1994. **4**: p. 27-43.
152. Anderson, D.L., K.M. Fisher, and G.J. Norman, *Development and Evaluation of the Conceptual Inventory of Natural Selection.* Journal of Research in Science Teaching, 2002. **39**(10): p. 952-978.

153. Bowling, B.V., et al., *Development and evaluation of a genetics literacy assessment instrument for undergraduates.* Genetics, 2008. **178**(1): p. 15-22.
154. Michael, J., et al., *The "Core Principles" of Physiology: What Should Students Understand?* Advances in Physiology Education., 2009.
155. Shi, J., et al., *An Introductory Molecular and Cell Biology Assessment.* CBE - Life Sciences Education., 2010. **9**(4).
156. Smith, M.K., W.B. Wood, and J.K. Knight, *The Genetics Concept Assessment: A New Concept Inventory for Gauging Student Understanding of Genetics.* CBE - Life Sciences Education., 2008. **7**(4): p. 422-430.
157. Morris, C.D., J.D. Bransford, and J.J. Franks, *Levels of processing versus transfer appropriate processing.* . Journal of Verbal Learning and Verbal Behavior, 1977 **116**: p. 519-533.
158. Holyoak, K.J., *Symbolic connectionism: Toward third-generation theories of expertise.*, in *Toward a general theory of expertise*, K.A. Ericsson and J. Smith, Editors. 1991, Cambridge University Press.: Cambridge, England. p. 301-336.
159. Steele, C.M. and J. Aronson, *Stereotype threat and the intellectual test performance of African Americans.* Journal of Personality and Social Psychology, 1995. **69**: p. 797-811.
160. Lewin, K., *A Dynamic Theory of Personality*. 1935, New York: McGraw Hill.
161. Dewey, J., *The school and society (Rev. ed.).* 1943, Chicago: University of Chicago Press.
162. Holliday, W.G., *Influential Research in Science Teaching: 1963-Present.* Journal of Research in Science Teaching., 2003. **40**(Supplement): p. v-x.
163. Piaget, J., *Science of education and the psychology of the child.* 1970, New York: Orion Press.
164. Ausubel, D., *The Psychology of Meaningful Verbal Learning.* 1963, New York: Grune and Stratton.
165. Dewey, J., *Democracy and Education*. 1916, New York: Macmillian.
166. Karplus, R., *Science teaching and the development of reasoning.* . Journal of Research in Science Teaching, 1977. **14**: p. 169-175.
167. Lawson, A., *A better way to teach biology*. American Biology Teacher., 1988. **50**: p. 266-278.
168. Lord, T., *A comparison between traditional and constructivist teaching in environmental science.* . The Journal of Environmental Education., 1998. **30**(3): p. 22-28.
169. Froyd, J., *Evidence for the Efficacy of Student-Active Learning Pedagogies*. 2008, Texas A&M University: College Station. p. 1-20.
170. Van Amburgh, J.A., et al., *A Tool for Measuring Active Learning in the Classroom.* American Journal of Pharmaceutical Education, 2007. **71**(5): p. 1-7.
171. Zimmerman, C., *The Development of Scientific Reasoning Skills.* Developmental Review, 2000. **20**: p. 99-149.
172. Siegler, R.S., *The origins of scientific reasoning. In R. S. Siegler (Ed.), Children's thinking: What develops?* . 1978, Erlbaum: Hillsdale, NJ. p. 109-149.
173. Schauble, L. and R. Glaser, *Scientific thinking in children and adults.* . Contributions to Human Development., 1990. **21**: p. 9-27.
174. Frantz, K.J., et al., *Routes to Research for Novice Undergraduate Neuroscientists.* CBE - Life Sciences Education., 2006.
175. Handelsman, J., *More women in science.* Science, 2005. **309**: p. 1190-1191.

176. Seymour, E. and N. Hewitt, *Talking about Leaving: Why Undergraduates Leave the Sciences.* 1997, Boulder, CO: Westview Press.
177. Balas, A.K. and J.R. Mascazine. *Using Field Experiences To Enhance College Science.* 1998.
178. Blackwell, W.H., M.J. Powell, and G.H. Dukes, *The Problem of Student Acceptance of Evolution.* Journal of Biological Education., 2003.
179. Findley, A.M., S.J. Lindsey, and S. Watts. *The Impact of Religious Belief on Learning in the Science Classroom.* 2001.
180. Hazel, E., M. Prosser, and K. Trigwell, *Variation in Learning Orchestration in University Biology Courses.* International Journal of Science Education., 2002.
181. Holschuh, J.P., S.L. Nist, and S. Olejnik, *Attributions to Failure: The Effects of Effort, Ability, and Learning Strategy Use on Perceptions of Future Goals and Emotional Responses.* Reading Psychology., 2001.
182. Hynd, C., J. Holschuh, and S. Nist, *Learning Complex Scientific Information: Motivation Theory and Its Relation to Student Perceptions.* Reading and Writing Quarterly: Overcoming Learning Difficulties., 2000.
183. Knight, J.K. and M.K. Smith, *Different but Equal? How Nonmajors and Majors Approach and Learn Genetics.* CBE - Life Sciences Education., 2010.
184. Metz, A.M., *The Effect of Access Time on Online Quiz Performance in Large Biology Lecture Courses.* Biochemistry and Molecular Biology Education., 2008.
185. Moore, R., *Attendance and Performance: How Important is it for Students to Attend Class?* Journal of College Science Teaching, 2003. **32**(6): p. 367-371.
186. Moore, R. and P.A. Jensen, *Join the Conversation: Are Students' Behaviors in College Classes Conditioned by their Experiences in High School?* The Learning Assistance Review, 2007. **12**(2): p. 47-55.
187. Moore, R. and P.A. Jensen, *Do Policies that Encourage Better Attendance in Lab Change Students' Academic Behaviors and Performances in Introductory Science Courses?* Science Educator., 2008.
188. Sinatra, G.M., et al., *Intentions and Beliefs in Students' Understanding and Acceptance of Biological Evolution.* Journal of Research in Science Teaching., 2003.
189. Thompson, T.L. and J.J. Mintzes, *Cognitive Structure and the Affective Domain: On Knowing and Feeling in Biology.* International Journal of Science Education., 2002.
190. Tomanek, D. and L. Montplaisir, *Students' Studying and Approaches to Learning in Introductory Biology.* Cell Biology Education., 2004.
191. Halloun, I. and D. Hestenes. *Views About Sciences Survey: VASS* 1996.
192. Jensen, P.A. and R. Moore, *Students' Behaviors, Grades and Perceptions in an Introductory Biology Course.* American Biology Teacher., 2008. **70**(8): p. 483-487.
193. Kruglanski, A.W., *Lay epistemies and human knowledge: Cognitive and Motivational Bases.* 1989, New York: Plenum.
194. Boyle, R.A., S.J. Magnusson, and A.J. Young. *Epistemic Motivation and Conceptual Change.* in *National Association for Research in Science Teaching.* 1993. Atlanta, GA.
195. Alexander, P.A., *The nature of disciplinary and domain learning. The knowledge, interest, and strategic dimensions of learning from subject matter text.*, in *Learning from text across conceptual domains* C. Hynd, Editor. 1998, Lawrence ErlbaumAssociates, Publishers: Mahwah, NJ. p. 263-287.

196. Alexander, P.A., J.M. Kulikowich, and S.K. Schulze, *How subject-matter knowledge affects recall and interest.* . American Educational Research Journal, 1994. **31**: p. 313-337.
197. Garner, R., *When children and adults do not use learning strategies: Toward a theory of settings.* . Review of Educational Research, 1990. **60**: p. 517-529.
198. Dweck, C.S. and B.G. Licht, *Determinants of academic achievement:The interactions of children's achievement orientations with skill area.* .Developmental Psychology, 1984. **20**: p. 628-636.
199. Bandura, A., *Self-efficacy: toward a unifying theory of behavioral change.* . Psychology Reviews, 1977. **84** p. 191-215.
200. Zimmerman, B.J., *Becoming a Self-Regulated Learner: An Overview*. Theory into Practice, 2002. **41**(2): p. 64-70.
201. Pintrich, P.R., *Motivational Beliefs as Resources for and Constraints on Conceptual Change.*, in *New Perspectives on Conceptual Change*, W. Schnotz, Vosniadou, S., and Carretero, M., Editor. 1999, Pergamon: New York.
202. Bloom, B.S., D.R. Krathwohl, and B.B. Masia, *Taxonomy of Educational Objectives: The Classification of Educational Goals.* 1956 New York, NY D. McKay.
203. Bowers, N., M. Brandon, and C.D. Hill, *The Use of a Knowledge Survey as an Indicator of Student Learning in an Introductory Biology Course.* Cell Biology Education, 2005. **4**(4): p. 311-322.
204. Khodor, J., D.G. Halme, and G.C. Walker, *A Hierarchical Biology Concept Framework: A Tool for Course Design.* Cell Biology Education., 2004.
205. Klymkowsky, M.W. and K. Garvin-Doxas. *Biology Concept Inventory*. 2008 [cited; Available from: www.bioliteracy.net
206. Biggs, J., D. Kember, and D. Leung, *The revised two-factor Study Process Questionnaire: R-SPQ- 2F*. British Journal of Educational Psychology, 2001. **71**: p. 133-149.
207. Bunce, D.M., et al., *Development of a Valid and Reliable Student-Achievement and Process-Skills Instrument.* Journal of College Science Teaching., 2010.
208. Crotwell Timmerman, B.E., et al., *Development of a 'universal rubric for assessing undergraduates' scientific reasoning skills using scientific writing.* Assessment and Evaluation in Higher Education., 2010: p. 1-39.
209. Lopatto, D., *Survey of Undergraduate Research Experiences (SURE): First Findings.* Cell Biology Education., 2004.
210. Ausubel, D.P., J. Novak, and H. Hanesian, *Educational Psychology: A Cognitive View* 1978 New York: Holt, Rinehart & Winston.