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Article

Implementing Recommendations for Introductory Biology by Writing a New Textbook

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We redesigned the undergraduate introductory biology course by writing a new textbook (*Integrating Concepts in Biology* [*ICB*]) that follows first principles of learning. Our approach emphasizes primary data interpretation and the utility of mathematics in biology, while de-emphasizing memorization. This redesign divides biology into five big ideas (information, evolution, cells, emergent properties, homeostasis), addressing each at five levels of organization (molecules, cells, organisms, populations, ecological systems). We compared our course outcomes with two sections that used a traditional textbook and were taught by different instructors. On data interpretation assessments administered periodically during the semester, our students performed better than students in the traditional sections ($p = 0.046$) and exhibited greater improvement over the course of the semester ($p = 0.015$). On factual content assessments, our students performed similarly to students in the other sections ($p = 0.737$). Pre- and postsemester assessment of disciplinary perceptions and self-appraisal indicate that our students acquired a more accurate perception of biology as a discipline and may have developed a more realistic evaluation of their scientific abilities than did the control students ($p < 0.05$). We conclude that *ICB* improves critical thinking, metacognition, and disciplinary perceptions without compromising content knowledge in introductory biology.

INTRODUCTION

This study reports on the efforts by three faculty (two biology and one mathematics) to implement national recommendations to improve the undergraduate introductory biology course by writing a new textbook from scratch. The authors measured the effectiveness of the intervention through content-based questions, quizzes based on data analysis and interpretation, and self-reported student attitudinal measures. The study centers on one section in comparison with two other sections that differed in the textbooks given to the students. Based on the results of this first assessment, the authors are encouraged to develop their textbook and associated resources and expand the book's adoption by many more campuses.

For more than 100 yr, educators have lamented the way introductory biology is taught to undergraduates (McEwing, 2003). Introductory biology for potential majors has been called antiquated and accused of chasing away students, especially students of color, who had been interested in the subject until they took their first college biology course (Mervis, 2010; Freeman *et al.*, 2011). Despite more than a century of recognized need for change, introductory biology courses have failed to evolve. More recently, efforts with substantial financial backing have focused on precisely what needs to change and why (National Research Council [NRC], 2003; American Association for the Advancement of Science [AAAS], 2011). Books have been published describing how biologists need

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Conflict of interest statement: A.M.C., L.J.H., and C.J.P. wrote the textbook described in this study and hope to publish it in the near future. Other books based on the same principles might accomplish the same outcomes, although no such book is commercially available at this time.
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to return to their roots and take a more scientific approach to their teaching (Wiggins and McTighe, 2005; Handelsman *et al.*, 2006). In particular, Handelsman *et al.* (2006) address three major areas in desperate need of reform: 1) active teaching in the classroom; 2) improved assessment that matches course goals; and 3) reverse engineering of courses that begins by listing learning outcomes and organizing the content after establishing the desired end point. Many papers have already documented improved learning through active-teaching strategies and improved assessment (summarized in Michael, 2006; Ueckert *et al.*, 2011), but we wanted to examine the role of a new textbook reverse-engineered to be in alignment with the recommendations of *BIO2010* (NRC, 2003) and *Vision and Change* (AAAS, 2011). Ueckert *et al.* (2011) spent 5 yr redesigning a large-enrollment introductory course but did not focus on the textbook in their reform effort. Three of us (A.M.C., L.J.H., and C.J.P.) decided to improve the content students read by reverse engineering an entire introductory biology textbook de novo, which we called *Integrating Concepts in Biology* (*ICB*). To evaluate the impact of the textbook, we limited our intervention to only the textbook for the purposes of this study.

It is important to understand the role textbooks play in student learning before writing a textbook. Textbooks are nearly universal in postsecondary science courses, in part because students find textbooks easier to read than primary literature (Besser *et al.*, 1999). Unfortunately, students do not always use the textbooks as their instructors intend. A majority of students do not read their assigned textbooks before coming to class (Clump *et al.*, 2004; Phillips and Phillips, 2007). Sikorski *et al.* (2002) found that most students read less than the rule-of-thumb 2 h for every 1 h of class time. The better students will read at a deeper level when they are confused, but weaker students either refuse to read or resort to memorization (Phillips and Phillips, 2007). Wade (1992) found that a textbook can increase the interest level of students but at the risk of impeding student learning. When asked about the most important aspects of a textbook, students overwhelmingly cite the quality of the writing as paramount. Student attention to the quality of writing raises the problem that most scientific data are presented graphically and not within the text. Even though graphic presentation can enhance learning (Evans *et al.*, 1987), the effectiveness of visual representations is dependent upon the learner's ability to independently and accurately interpret the figures (Downey, 1980). Students need to be taught visual literacy, just as they need to be taught how to read and write (Glasgow, 1994).

Crucial to this study is the structure of *ICB*, which was the primary intervention. The three textbook authors participated in phase I of the Advanced Placement (AP) Redesign Commission (College Board, 2012) and the *Vision and Change* (AAAS, 2011) national efforts to reduce the volume of content and focus on the "big ideas," or themes, of biology. From this starting position, the authors focused on five big ideas of biology: information, evolution, cells, emergent properties, and homeostasis (Figure 1). The authors also wanted to address a common misconception about biology that college students subconsciously internalize, namely, that biology is divided into two major divisions of small (cell and molecular) and big (organismal and ecological) biology. The small versus big divide is most pronounced in graduate programs, and this unnatural division of life is institutionalized when undergraduates specialize by majoring in biochemistry or ecology, despite the living world's interdigitated nature. Therefore, each of the five big ideas needed to be addressed equally at five scales of organization: 1) molecular; 2) cellular; 3) organismal; 4) population; and 5) ecological system, which includes communities and ecosystems. The five big ideas and the five levels of organization determined that the yearlong course would be presented in 25 chapters of the new textbook.

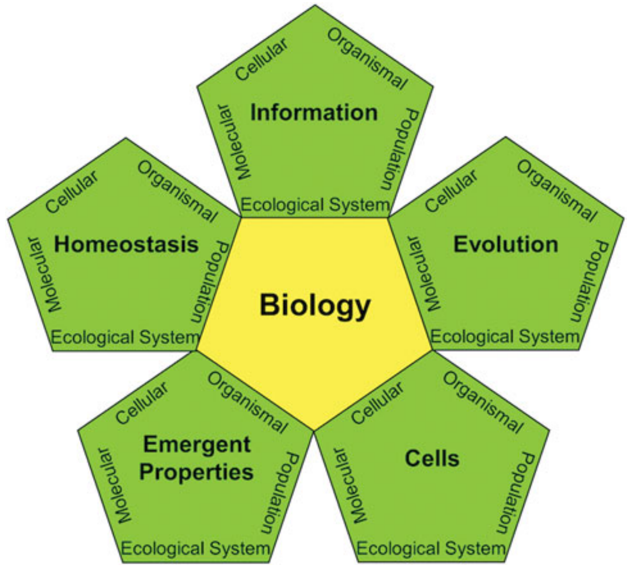

Figure 1. Structural organization of *ICB* and course content with five big ideas (green pentagons) and five levels of size scale for each big idea.

One key component of *ICB* is the substantial reduction in the presentation of highly specific information that can overwhelm students and obscure the science of biology. *BIO2010* (NRC, 2003) and the *Vision and Change* document (AAAS, 2011) highlight an attitudinal difference between what students experience and what professional biologists actually do in their jobs. Beginning with high school and continuing through college, biology students are required to memorize large amounts of material. Although professional biologists appear to enjoy coining new terms and acronyms (Schatz, 2012), they are not paid to memorize vocabulary words. Memorization of vocabulary by students emphasizes names of species, body parts, molecules, and habitat types given unique names by experts in their fields. Bravo and Cervetti (2008) reported that introductory biology students learn more vocabulary words than students taking an introductory foreign language course. An overemphasis on vocabulary and memorization is not a new problem. Stevenson (1937) reported that foreign language teachers thought students were doing very well if they acquired 800–1000 new words, but biology students were typically asked to learn ~1400 new terms. However, most professional biologists only have a working vocabulary in a small slice of the overall biology vocabulary pie. The *ICB* authors established a rule in their writing that jargon would be minimized, and new terms would be introduced only if the term is used at least three times in the textbook.

Another key component of *ICB* was to teach students how to analyze and interpret data. Professional biologists earn their livelihoods by asking questions, designing and conducting experiments, and interpreting data, the sum of which could be called "the process of science." Textbooks typically emphasize content and factoids, rather than the activities practiced by professional biologists. In a recent study, Duncan *et al.* (2011) documented that, on average, <5% of all figures in introductory biology textbooks address the process of science. A quick examination of introductory biology textbooks will reveal most figures provide the take-home message, and students do not get to practice analysis and interpretation. If experimental results are presented, they are often redrawn and cleaned up, so the results barely resemble the originally published data.

ICB addresses the process of science, as well as the limits of our understanding. Surveys of our students revealed their belief that the big questions about life have all been answered and all that is left for biologists is to fill in the details. They accepted the small versus big scale divide of biology departments as a reflection of nature. Furthermore, students often overestimate their biological knowledge and believe they are more capable than objective measures indicate (Mabe and West, 1982; Sundberg and Moncada, 1994; Kruger and Dunning, 1999; Dunning *et al.*, 2004). The *ICB* authors wanted students to rediscover biology as a science based on inquiry and to realize the vastness of the unknown compared with the known.

ICB incorporates mathematics in every chapter in the context of biological research questions. Summarizing many previous studies, *BIO2010* (NRC, 2003) and *Vision and Change* (AAAS, 2011) described the importance of mathematics to enhancing biology students' understanding of life. To prepare our students for careers in a competitive global market, biology courses need to help students understand the importance of quantitative reasoning. To facilitate this goal, we developed BioMath Explorations (BMEs) in *ICB*, which apply typical high school math skills to enrich biological understanding. To maximize the potential audience of the BMEs, we assumed students had not taken a calculus course. Mathematics, computer science, statistics, and probability are all important tools that professional biologists, physicians, and public health workers use daily to perform their jobs.

Because writing a new textbook for introductory biology was the major innovation for this study, the authors took great care in its construction. Once all the components were enumerated (i.e., five big ideas explored over the scale continuum, mathematics to enhance biology understanding, and incorporation of the process of science), we consulted the cognitive psychology literature that documents the first principles of learning (NRC, 2000, 2012; Ambrose *et al.*, 2010; Slater *et al.*, 2011). We know that people learn best if they construct their own knowledge, which is optimized with guided constructivism (Fosnot, 1996; Schwartz and Fischer, 2003). Therefore, the text and figures in *ICB* provide students with the necessary data and background to assemble their own understanding, rather than memorizing simple take-home messages. The book was designed to facilitate students' discernment of the main points based on data provided in figures and tables that appear as they did in the original scientific papers. Students recapitulate the same process professional biologists undertook to infer how life functions from experimental data.

In addition to constructing their own knowledge to maximize retention and understanding, people learn best if they can associate the new information with something they already understand (NRC, 2000). This ability to link new information is what distinguishes a novice from an expert, because experts readily connect new and old information to facilitate retention and context (Hamblin, 2010; NRC, 2012). To help students realize that the biology they are learning is connected to their daily lives, *ICB* provides vignettes of ethical, legal, and social implications (ELSI). The short ELSI stories appear in every chapter within the relevant portion of the text, rather than at the end of a chapter.

The textbook authors spent 3 yr collecting appropriate case studies and writing the text. This paper describes a yearlong study of the first students to use *ICB*. The intervention used in this study was the *ICB* textbook, which students in the experimental section read, while students in the two comparison sections used a traditional textbook. All three sections assessed in the study were conducted in similar ways, with a modified Socratic method featuring a mixture of some lecture and some question-and-answer sessions between teachers and students. The multi-tiered assessment was designed to address content understanding and retention, data interpretation skills, and student attitudes toward biology as a discipline. *ICB* is a direct response to both *Vision and Change* (AAAS, 2011) and *BIO2010* (NRC, 2003), both of which called for improvements over traditional textbooks.

METHODS

Experimental Design

This study was conducted during the 2010–2011 academic year at Davidson College, a liberal arts college in North Carolina with nearly 2000 undergraduates and no graduate students. Class sizes are limited to 32 students, and the same instructor teaches the lecture and laboratory portions of the introductory biology courses. The key intervention was the use of a new textbook (*ICB*) written by three of the authors (A.M.C., L.J.H., and C.J.P.). One section of Biology 111 used the *ICB* textbook and was taught by one of the authors (A.M.C.), while the two control Biology 111 sections (hereafter referred to collectively as "traditional") used a traditional commercial textbook and were taught by two other instructors (neither of whom is an author on this paper). Biology 111 is the first half of a two-semester sequence of courses intended for potential majors, premedical students, and others interested in the sciences. Biology 111 focuses on cell and molecular biology, while the second course (Biology 112) focuses on organismal, population, and ecological systems biology. We obtained institutional review board exemption for the entire study (proposal #2010–074).

The classroom activities for the experimental section were not changed from previous iterations of Biology 111 and were very similar to the two traditional sections. All three instructors use a modified Socratic method, with some presentation of material in conjunction with questions and answers. The design of this experiment focused on only one variable for the comparison, the textbook used by students.

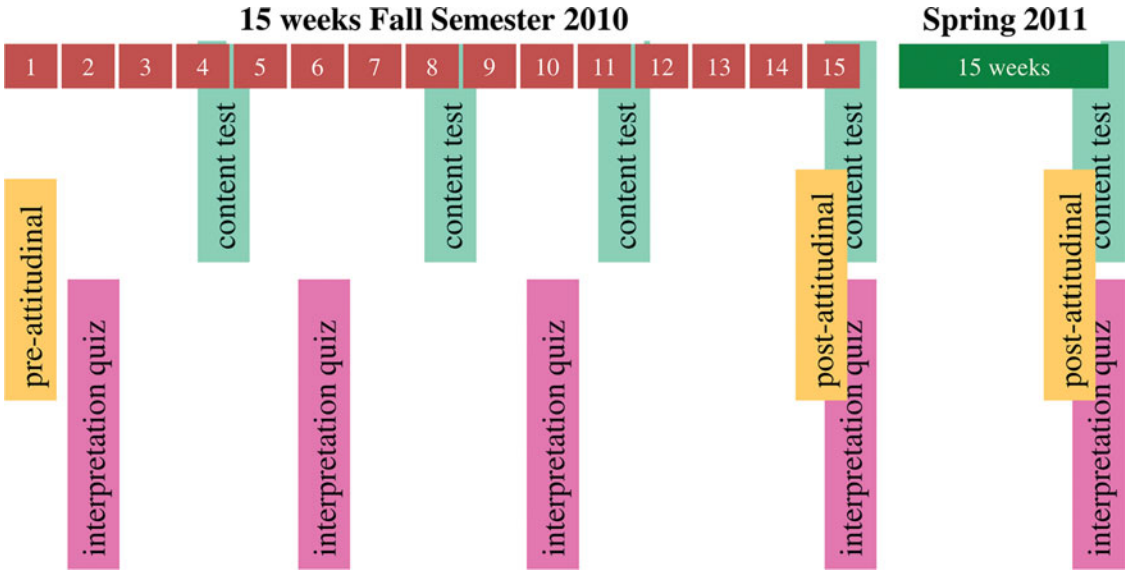

Figure 2. Timeline for administration of assessments described in this study. A full set of assessment questions is available in the Supplemental Material.

The other two traditional sections used an in-house–produced study guide in conjunction with a traditional textbook (Sadava *et al.*, 2011). The study guide and laboratory manual for the traditional sections are available online (www.bio.davidson.edu/courses/bio111/studyguide.html). The instructor using *ICB* (A.M.C.) had used a traditional textbook and the study guide for the previous 16 years. The lecture schedule for the Fall 2010 *ICB* class is available online (www.bio.davidson.edu/people/macampbell/111/Bio111reading_F2010.html).

Students completed several types of assessment (Figure 2) presented in this study. Students provided information about their perceptions of biology and themselves at the beginning of the Fall semester and at the end of both Fall and Spring semesters. They submitted graded responses to content questions four times during the Fall semester and at the end of Spring semester. Students also submitted ungraded responses to the interpretation quizzes four times during the Fall semester and at the end of Spring semester.

Participants

None of the students knew they were part of an experiment when they enrolled in the course. They chose their Biology 111 sections prior to the beginning of class for personal reasons (e.g., time of day, conflicts with other classes), and thus did not select one section over another based on the type of textbook used. Students learned of the new approach for the *ICB* course during the first day of class and could drop the class within 1 wk without penalty. All three courses met Monday, Wednesday, and Friday for 50 min in a 15-wk semester. The laboratory sections met once a week for 2 h and 45 min, and all lab sections followed the same locally produced laboratory manual. Class size was limited to 32 students in the lecture portion, with 16 students in each of two laboratory sections, also taught by the same lecture instructors. One section of 30 students used the new *ICB* textbook (two students dropped the course during the first week). Two other traditional sections totaling 63 students used a traditional introductory biology textbook. For all 93 students, the only intervention distinguishing the experimental section was the textbook used in the lecture portion of the class and the associated content presentations and discussions. It is important to realize that, at a small school, word of mouth spreads information about new courses quickly. Therefore, it would be impossible to repeat this again at Davidson College, since incoming students will not choose their sections naively after the Fall of 2010.

Materials

Textbook Development. The *ICB* textbook is a significant departure from traditional texts in many important ways. The pedagogical design of the book focuses on five big ideas—information, evolution, cells, emergent properties, and homeostasis. Each of the big ideas is addressed at five levels of organization–molecular, cellular, organismal, population and ecological systems. *ICB* is composed of 25 chapters intended to be covered over a typical academic year (two semesters or three quarters). Sample chapters are available upon request from the authors (A.M.C., L.J.H., and C.J.P.).

ICB uses original figures from published research, rather than stylized or rendered figures with "thought bubbles" providing students with textbook-generated take-home messages. *ICB* students are provided with an overarching question and sufficient background material in each chapter to enable them to interpret the figures and tables themselves. Integrating Questions (IQs) are scattered throughout each section of every chapter to focus student attention on key aspects of the data. Following the IQs, students read summary text to highlight the main lessons from the figures, but the IQs are not directly answered in a way that might circumvent students' constructing their own knowledge. At the end of each chapter is a series of review questions to help students remember the major topics within a chapter. Approximately five Apply What You Know questions follow the review questions, and these application questions encourage students to use Web-based resources to make connections between the different levels of organization covered in other chapters.

Within each chapter are two additional pedagogical features–the BMEs and the ELSI vignettes. Each chapter contains one to three BMEs that explore mathematical ways to enrich biological understanding and require familiarity only with algebra and arithmetic, not calculus. BMEs are always tied to the biological content and are presented as boxed material, and though they enrich students' understanding of biology, they are not required to understand the biology. ELSIs help students see the connection between the material they are learning and the world around them. ELSIs appear in boxes and are related to the material or questions raised in that section of the chapter.

In class, students were shown annotated PowerPoint slides that contained the figures from *ICB*. These figures are designed to help students learn how to analyze and interpret scientific data. The annotations typically began with most of the figure covered and then gradually revealed over time. All of the figures were available online to students, but the annotation slides were not made available electronically. Sample annotated PowerPoint slides are available upon request from the *ICB* authors.

Content Tests. We administered a series of 16 multiple-choice questions to both student populations. These questions were similar to ones that might appear on an exam in a typical introductory biology course (see Supplemental Material for questions). The questions were written to highlight the material covered in the traditional classrooms, and all the authors of this study and the two additional instructors participated in their construction, with the three Biology 111 instructors administering the questions.

Interpretation Quizzes. The second component of our assessment examined potential improvement in student ability to think critically about novel biological data. We presented students with figures from original research articles dealing with topics not presented in any of the three sections. The questions provided adequate explanation of context and description of the techniques used, and listed possible interpretations of the results shown (see Supplemental Material for example questions). We asked students to indicate whether each interpretation was valid or invalid, given just the data and experimental description provided. Five to 10 possible conclusions were listed for a particular piece of data, and students had to evaluate each statement as either true (valid conclusion from the data provided) or false (invalid conclusion or not one that follows strictly from the data provided). The questions were written with input from all the authors of this study plus the two additional instructors, with the three Biology 111 instructors administering the questions. Each of the four interpretation quizzes was presented to the students electronically during the same week of the semester in all six laboratory sections. These quizzes did not contribute to student grades for the course. A complete set of quizzes is available in the Supplemental Material.

Attitudinal Surveys. The survey asked students to rate their biology abilities or level of agreement with a statement about biology on a five-point Likert scale. These surveys were developed by the authors of this study with input from the two instructors of the control sections. Complete surveys are available in the Supplemental Material.

Procedures

Textbook and Classroom. The *ICB* textbook has not been published yet, so students used a manuscript format printed locally with figures printed in color and provided as a separate bundle of pages. Electronic PowerPoint slides of figures and tables from the textbook were available to the students, although most preferred to write directly on the printed color figures. Only half the chapters, those dealing with the big ideas at the molecular, cellular, and a portion of the organismal scale, were used in this study (see the complete reading schedule online at: www.bio.davidson.edu/people/macampbell/111/Bio111reading_F2010.html). Students read chapters addressing material similar to that covered in the two traditional Biology 111 sections, which are defined by size scale alone (molecular and cellular), as is typical of most introductory biology courses.

Assessment Tools. The content questions were presented as graded items on each of the four exams given in all three sections. The questions were presented to the students after they learned the appropriate material, but the material was not presented in the same order to the *ICB* students as it was in the two traditional sections. Interpretation quizzes were administered during the semester, each one featuring data figures or tables from two or three different experiments and a total of 10–20 possible conclusions to evaluate as true or false (see *Materials*). Students from all three sections took the same ungraded data interpretation quizzes during the same weeks of the semester (see Figure 2). Attitudinal surveys were presented to students electronically during the first week of the semester and again during the last week of the semester. These were not graded or rewarded with extra credit points.

Longitudinal Assessment. After letting one full semester pass, during which most of our students took their second semester of introductory biology (Biology 112) using a traditional textbook, we assessed the students again, using modified versions of all three of the assessment components described above. For content knowledge, a four-question subset of the original 16 multiple-choice questions was used, consisting of the two questions on which students originally performed best and the two questions on which students originally performed worst. For data interpretation, two new data figures from a paper not previously used were selected and introduced, with a list of 14 possible conclusions for the students to evaluate as valid or invalid. Finally, a modified version of the attitudes survey was administered, with some added questions asking the students to compare their first- and second-semester introductory biology experiences.

Analysis

Neither the *ICB* textbook authors nor the faculty teaching the two control Biology 111 sections participated in the analysis of assessment data presented in this study. Two authors of this study (M.J.B. and P.J.S.) were responsible for analyzing student outcomes, although all five authors participated in their interpretation.

Content Tests. Aggregate performance on the 16 content questions by students in the *ICB* section and traditional sections was compared using Student's t test.

Interpretation Quizzes. Interpretation quizzes represented an assessment of skills and competencies that were not tied directly to any specific content knowledge covered in Biology 111. The data were analyzed on a quiz-by-quiz basis, rather than as an aggregate of performance over the entire semester. Chronological analysis of quizzes allowed for tracking improvement in performance on this type of interpretation competency over the course of the semester. We compared the performance of students using *ICB* and the traditional textbook by two-way analysis of variance plus Tukey-Kramer post hoc comparison of means, in which teaching approach and quiz number were the fixed-effects factors. We also estimated a regression model for *ICB* versus traditional students to evaluate whether their interpretation skills (as indicated by the percentage of correct responses) changed over the course of the semester and these four quizzes. In the model for each group of students, the observations are composed of each student's score on each quiz; participating in all four quizzes would give a student four distinct scores (and four observations) in the data set. The regression model's sole independent variable is the number of the quiz, ranging from one to four. If the interpretation skills of a group changed from the first to the fourth quiz, the independent variable's regression coefficient would be significantly different from zero (indicating a non-zero slope).

Attitudinal Surveys. For the attitudinal surveys, we calculated the average response to questions at the start of the semester separately for the two populations of students. For each question, a t test indicated whether the average responses differed significantly between the two groups on this pretest. We then calculated for each student the change in response to a question from the start to the end of the semester. A positive value indicated that the student's response increased numerically on the response scale; a negative value indicated a decrease. For each prompt, we calculated the average change for each group of students. As before, a t test determined whether the two groups differed significantly in the average change in their responses from the beginning to the end of the semester or the end of the Spring semester for the longitudinal assessment (see below).

Longitudinal Assessment. Students in all three sections were asked to complete a final assessment at the end of the Spring term, 2011 (see *Procedures*). The students were not given any incentive to complete this final assessment, since they were not enrolled in courses offered by the authors of this study or the two control instructors. Each of the three snapshot longitudinal assessments (attitudinal, interpretation, and content) was analyzed by t test or, when appropriate, Fisher's exact test.

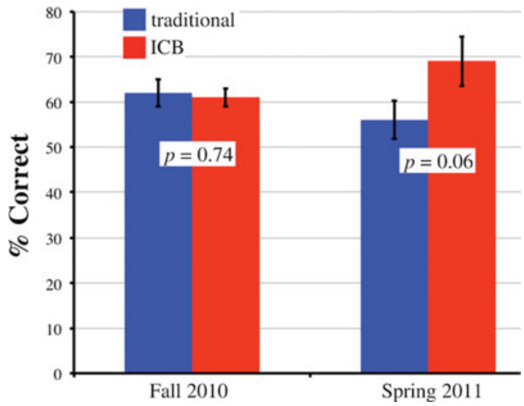

Figure 3. Content knowledge testing. In the Fall of 2010, students in all three sections answered 16 multiple-choice questions as part of graded tests. In April 2011, the same students were asked a subset of the same questions. Percent correct is the average of student scores. Error bars represent SE of the mean.

RESULTS

Content Tests

To address the concern that *ICB*'s emphasis on interpreting original biological data to develop conceptual understanding (i.e., the scientific process) resulted in students learning less factual content compared with their peers using a traditional textbook, we asked both student populations a series of multiple-choice questions characteristic of a traditional introductory biology exam. Performance on this series of questions indicated that during the semester there was no significant difference between the two groups of students in their ability to answer questions requiring factual recall based on knowledge and comprehension (Bloom's levels 1 and 2; Bloom, 1956). Students using *ICB* averaged 60.1% correct, and students in the traditional approach averaged 61.8% correct, on these questions ($t = 0.336$, df $= 89$, $p = 0.737$; Figure 3). Using *ICB*, in which a smaller volume of information is presented and in which students construct their own knowledge, does not lessen students' ability to learn and remember traditional biology content.

We assessed both populations of students in the last week of the following (Spring) semester with responses from 25 of the 30 *ICB* students and 40 of the 63 traditional students. Most of these students were completing their second semester of introductory biology (Biology 112). As shown in Figure 3, the *ICB* students performed better on these content knowledge questions than the students using a traditional textbook (68.8% vs. 55.8% correct). The difference in Spring 2011 responses has a p value of 0.062 ($t = 1.90$, df $= 61$), which, though not significant, suggests that students using *ICB* may tend to retain more of the factual content knowledge than the traditionally taught students 4 mo later.

Interpretation Quizzes

To determine how students using different textbooks compared with regard to their quantitative analysis and data interpretation skills, we asked students to examine real research data and evaluate the validity of a number of possible interpretations of the results. We administered four sequential

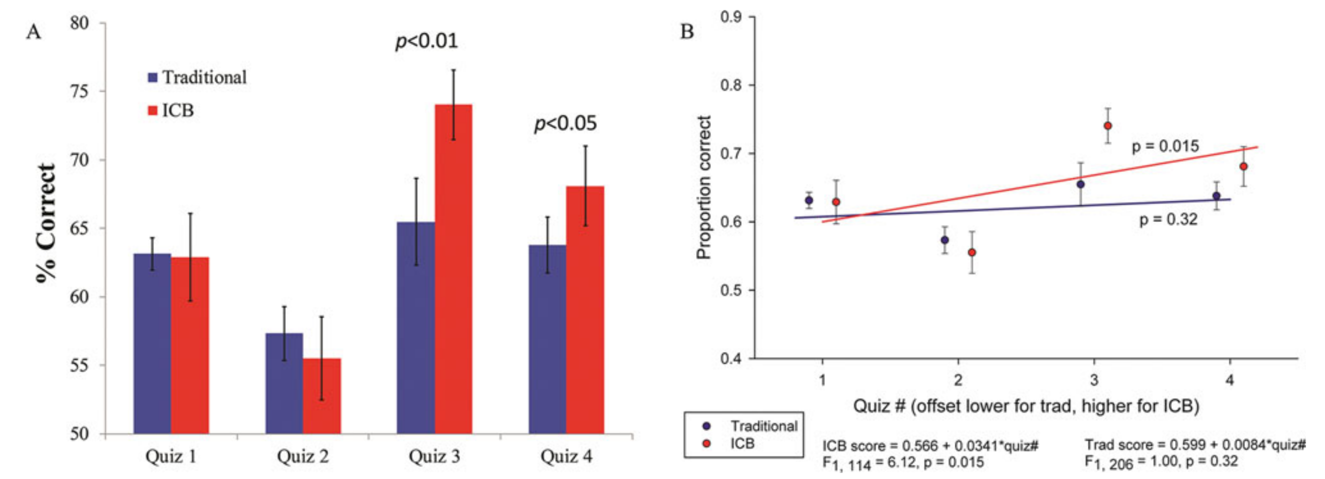

Figure 4. Data interpretation testing. In the Fall of 2010, students in all three sections took an ungraded assessment of data interpretation skills during laboratory sessions. (A) Percent correct is the average of aggregate student scores in *ICB* or traditional sections. Error bars represent SE of the mean. Main effect of teaching approach was significant ($p = 0.046$), with significant differences in performance on both quiz 3 and quiz 4, as indicated. (B) Regression models of performance on data interpretation assessments are shown as linear trend lines. Data points displayed are the same averages depicted in part A, but the regression lines are based on individual student scores. p values denote the likelihood that scores remained unchanged over time (i.e., if trend line had zero slope).

rounds of interpretation skills assessment over the course of the semester, denoted as quizzes 1 through 4 (Figure 4A). Students using *ICB* averaged 62.9%, 55.5%, 74.0%, and 68.1% on these quizzes, while those using a traditional textbook averaged 63.1%, 56.4%, 65.5%, and 63.8%, respectively. Analysis of these results indicates a significant effect of *ICB* on performance ($F_{1,\,317} = 4.0$, $p = 0.046$), with *ICB* students performing significantly better than traditional students on quiz 3 ($p < 0.01$) and quiz 4 ($p < 0.05$; Figure 4A).

A regression model applied to the scores of individual students in each of the teaching approaches reveals that students using *ICB* significantly improved from the first to the fourth data interpretation quiz ($F_{1,\,114} = 6.12$, $p = 0.015$), while students using the traditional textbook did not significantly improve over the same time period and on the same questions ($F_{1,\,206} = 1.00$, $p = 0.320$; Figure 4B). Note that the two populations of students were indistinguishable at the beginning of the semester, which rules out the possibility of *ICB* students starting at a higher capacity before the semester began. Taken together, these data show that students who used *ICB* improved in their ability to analyze novel data, which reflects higher levels of thinking, such as application, analysis, and synthesis (Bloom's levels 3, 4, and 5; Bloom, 1956). Students using a traditional textbook did not show significant improvement over the course of the semester, with the regression line being indistinguishable from a horizontal line.

The difference between the two student populations in analysis and interpretation skills disappeared one semester later, when we assessed the students near the end of the Spring semester on their ability to interpret experimental data. Students who had used *ICB* scored 63.1% correct, while those previously in the traditional sections scored 63.6% correct ($t = 0.105$, df = 55, $p = 0.917$). The similarity in performance on these analytical questions over the long term suggests that without sustained practice of data analysis and interpretation, students lose the skills they gained when using *ICB* and the advantage they had over the traditional students.

Attitudinal Surveys

We surveyed students at the beginning and end of the Fall 2010 semester to determine their perceptions of biology as a discipline and of themselves as biologists. The end-of-semester version of the survey was similar to the early semester version, but the former also asked questions about the course they had just completed, which included some free-response evaluations of their experience with the course. We also administered a modified version of the survey at the end of the following semester, after the students had nearly completed a traditionally taught biology course. This survey at the end of Spring semester was administered at the same time as the longitudinal assessment of content and data interpretation described above.

Students using the two different textbooks diverged significantly in their perceptions of several key areas over the course of the semester (Table 1). For example, students using *ICB* self-assessed their ability to "understand the most central concepts of biology" with a significantly smaller increase over the semester (+0.12) than students who used a traditional textbook (+0.53, $t = 1.71$, df = 59, $p < 0.05$). Meanwhile, in rating their own ability to "apply biological concepts to new problems and data" and to "analyze biological data that I have not seen before," students who used *ICB* happened to start the semester with significantly higher self-assessments than the traditional students ($t = 3.57$, df = 71, $p < 0.001$; and $t = 2.94$, df = 71, $p < 0.01$, respectively), but in both cases rated themselves weaker at the end of the semester than at the beginning (−0.04 and −0.28, respectively). In contrast with the *ICB* students, those who used a traditional textbook rated themselves stronger at the end of the semester than at the beginning (+0.67 and +0.56, respectively). These changes in post- versus pretest ratings were significantly different when comparing the two groups of students ($t = 2.67$, df = 59, $p < 0.01$; and $t = 2.95$, df = 59, $p < 0.01$, respectively). Differences in self-perceived ability existed despite the fact that *ICB* students performed significantly better on the data

Table 1. Self-evaluation of analytical skills[a]

1–5 scale, 1 = weak	Average at start		Δ in average at end	
	ICB	Traditional	*ICB*	Traditional
Understand central concepts of biology	4.11	3.76	+0.12*	+0.53
Apply concepts to new situations	3.89***	3.09	−0.04**	+0.67
Analyze new data	3.68**	3.02	−0.28**	+0.56

[a] At the beginning and end of the Fall 2010 semester, attitudinal surveys asked students in all three sections to rate themselves on a number of analytical abilities. See Supplemental Material for precise wording of prompts.

*$p < 0.05$.

**$p < 0.01$.

***$p < 0.001$.

interpretation assessment than did the traditional approach students and were statistically equal to the traditional approach students on the content knowledge assessment during the semester (Figures 3 and 4).

The survey also probed student perceptions of biology as a discipline (Table 2). When asked to rate the accuracy of the statement, "Biology is a set of definitions and processes to learn," students in both treatments initially were indistinguishable, but by the end of the semester, those using *ICB* gave a lower rating at the end of the semester than at the beginning (change of −0.58), while traditional students gave a higher rating at the end of the semester than at the beginning (change of +0.50). These changes in pre- versus posttest rating were significantly different between the two groups of students ($t = 3.57$, df = 58, $p < 0.001$). The two populations retained their significantly different perceptions in the longitudinal assessment (changes of −0.46 and +0.45 compared with original rating, $t = 3.35$, df = 51, $p < 0.001$), despite both having taken the second semester of introductory biology, which employed the traditional approach.

When initially asked to respond to the prompt, "Biology is a discipline where all the big questions have already been answered," the two populations responded similarly. As shown in Table 2, however, *ICB* students agreed with the statement less after the first semester (change of −0.32), while students using the traditional textbook agreed more (change of +0.22) after the semester, representing a significant difference in pre- to postsemester changes between the two groups ($t = 2.37$, df = 59, $p < 0.05$). This difference between the two groups was diminished after the second semester (−0.33 vs. 0.00, $t = 1.54$, df = 51, $p = 0.06$).

At the initial assessment, both groups similarly agreed with the statement, "Division of biology into large (organismal, ecological, etc.) and small (molecular, cellular, etc.) fields of study accurately reflects the division in the natural world." Students using *ICB* disagreed with this statement significantly more at the end of the Fall semester (change of −1.08) than students using a traditional textbook (change of −0.06, $t = 3.46$, df = 58, $p < 0.001$; Table 2). The difference in perceptions of big versus small biology persisted at the end of the Spring semester (change of −0.75 for *ICB* students vs. change of −0.10 for traditional students) and remained statistically significant ($t = 2.44$, df = 51, $p < 0.01$).

At the beginning of the Fall semester, when asked "How important is memorization for biologists to be successful?," students in both groups agreed that memorization was very important. After the semester using *ICB*, the *ICB* students rated the importance of memorization much lower than they had at the beginning (change of −1.48), while traditional students rated the importance only slightly lower (change of −0.08; Table 2). These changes in ratings were significantly different from each other ($t = 6.78$, df = 59, $p < 0.001$) and persisted through the end of the Spring semester (*ICB* students changed −1.27, while traditional students changed +0.23, $t = 5.96$, df = 51, $p < 0.001$).

Table 2. Student perceptions of biology as a discipline

1–5 scale, 5 = extremely accurate	Average at start of Fall		Δ in average end of Fall		Δ in average end of Spring	
	ICB	Traditional	*ICB*	Traditional	*ICB*	Traditional
Biology is definitions and processes	2.86	2.61	−0.58***	+0.50	−0.46***	+0.45
Big questions of biology are already answered	1.71	1.50	−0.32*	+0.22	−0.33^	0.00
Big/small division of biology describes nature	3.15	3.02	−1.08***	−0.06	−0.75**	−0.10
1–5 scale, 5 = extremely important						
Memorization	3.96	3.64	−1.48***	−0.08	−1.27***	+0.23

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

^ $p = 0.06$.

Table 3. Retrospective responses of Biology 111 students

Prompt	*ICB* students	Traditional students	Significance level
Was Biology 111 fundamentally different from previous courses?	88% said "yes"	63% said "yes"	$p < 0.05$
Was Biology 111 fundamentally different from Biology 112?	15/25 (60%) said "yes"	17/40 (42.5%) said "yes"	$p = 0.2075$
For those who answered "yes" above, did Biology 112 require more memorization than Biology 111?	12/15 (80%) said "yes"	2/17 (12%) said "yes"	$p = 0.0002$

When asked at the end of the Fall semester "Was this semester's biology course fundamentally different from previous biology courses you have had?", 88% of *ICB* students said "yes," compared with 63% of traditional approach students (t = 2.31, df = 65, $p < 0.05$; Table 3). The reference courses for these introductory students were self-defined and probably consisted of their biology courses in high school or perhaps other biology experiences they had before taking Biology 111. The high percentage of traditional students responding "yes" to this question indicates that our traditional sections of introductory biology are not very traditional, but are in fact significant departures from courses such as AP Biology, in which the content is extensive, and memorization is especially important. In the longitudinal assessment, when 25 *ICB* students and 40 traditional students responded to prompts that asked whether their Spring semester Biology 112 course was fundamentally different from the Fall semester Biology 111 course, 15 (60%) *ICB* students and 17 (42.5%) traditional students said "yes." Of those who responded "yes," 80% of the *ICB* students, but only 12% of the traditional students, said that Biology 112 required more memorization than Biology 111 (Table 3; $p = 0.0002$ by Fisher's exact test).

Finally, Table 4 provides a selection of free-response comments collected from Fall semester course evaluations completed by *ICB* students. These comments are similar to many others gathered from *ICB* students' course evaluations. It is evident from these quotes that students greatly appreciated the decreased memorization, emphasis on critical thinking, and increased applicability and contextualization they experienced in the *ICB* section compared with their previous experiences in science courses.

DISCUSSION

The results of this study indicate that the new guided constructivist approach of a textbook in undergraduate introductory biology enhances student acquisition of critical competencies and metacognitive awareness without compromising traditional content knowledge. *ICB* emphasizes: the scientific process that led to biological understanding; students constructing their own knowledge from original research data; quantitative analysis and interpretation; relevance of biology to everyday experience; and reducing the volume of content memorization. Moreover, students reported satisfaction and excitement with *ICB*. Open-ended student comments indicated students gained a broader perspective in biology and transferability of critical thinking and analytical skills to other courses.

One of the concerns and criticisms with employing the scientific process in *ICB* was that students would not gain the necessary content knowledge, basic vocabulary, and foundational details that most educators see as crucial to the introductory biology experience. However, many recent research publications and calls to improve the way undergraduate biology is taught present the opposite point of view (NRC, 2003; AAAS, 2011). There is wide agreement that focusing on minutiae to the exclusion of the "big picture" and critical competencies has proven ineffective for many students. Focusing on content has become a particular concern, as the volume of biological information, along with the amount of jargon and heft of introductory textbooks, have expanded tremendously in recent decades. Students that used *ICB*, however, performed just as well as their traditionally taught peers on typical introductory biology multiple-choice content questions (Figure 3). In fact, there is a trend of improvement, though not strictly significant, in long-term retention of content knowledge in students taught with this approach. Consistent with previous reports, cultivating critical thinking and firmly rooting biological concepts in their context allows students to make meaningful connections that strengthen their understanding and recall of previously learned material. Recursive learning on one's own when connections to previously learned material are triggered by later contexts is another hallmark of the development of disciplinary expertise (NRC, 2000).

Also central to the calls for undergraduate biology reform has been the assertion that students should be more proficient with quantitative reasoning and understanding and interpreting experimental data. *ICB* introduces students to the big ideas of biology through the use of data figures and tables from original research literature and guides them through the analysis and interpretation of these real experimental results. This technique taught students how to examine, think about, and understand these results, which they apply

Table 4. Anonymous *ICB* student quotes given in response to open-ended course evaluations

"The method of learning, placing emphasis on the interpretation of data, has helped me not only in this class, but also in others."

"I found it much more beneficial using this approach compared with straight memorization. It allowed me to gain interpretation skills I was lacking before."

"The data-driven approach is brilliant. It alleviates the issues that I've always had of asking, 'How do we know that? What's the supporting data?'"

"Emphasis on big picture and understanding how to pull information from real data were an easier and more beneficial format than memorization of facts (which used to be a struggle for me)."

significantly better than traditional students (Figure 4). Perhaps it should not be surprising that *ICB* students performed better on interpretation skills questions, since they had substantial practice interpreting data during their reading and classroom sessions. Importantly, our results demonstrate that students were able to apply what they learned to new situations and unfamiliar data and to do so more effectively over time. The traditional students were less effective in performing this kind of analysis and interpretation, and did not improve over the semester (Figure 4). The data indicate that students do not develop analytical skills when they use a traditional textbook in which most ideas are delivered as "handed-down" knowledge. For introductory biology students, learning data analysis skills appears to be more like learning a language than learning to ride a bike, in that the gains from the Fall semester were not sustained through the Spring semester in the absence of continued practice. Data interpretation skills require regular practice for more than just one semester in order to retain them over the long term.

Additional benefits of *ICB* became evident from our pre- and postsemester surveys of students' perceptions of biology and their own scientific abilities, which are also supported by collected student comments (Tables 1–4). Although *ICB* student responses were unchanged, the traditional student responses changed after the second semester (from +0.22 to 0.00) when asked whether all the big questions have already been answered (Table 2). It appears the Spring semester of Biology 112, which focused on "big biology," helped those students realize how unanswered questions still exist in biology. *ICB* students, who collectively performed better in the skills survey (Figure 3) and retained content information longer (Figure 2), were less confident in their ability than the traditional students (Table 1). However, a disconnect between novices' self-reporting and actual ability is well documented (Mabe and West, 1982; Sundberg and Moncada, 1994; Dunning *et al.*, 2004; Gross and Latham, 2007). The student perception data suggest that students using *ICB* developed greater metacognitive awareness of their scientific abilities and limitations. The students using *ICB* understood their own limitations, an indication of critical introspection and progress in the transition from novice toward expert that we strive to foster in students (Mabe and West, 1982; Dunning *et al.*, 2004; Gross and Latham, 2007). It appears that the *ICB* students may have developed a more humble perspective on their own ability as a result of the constructivist approach and their struggles interpreting data. Collectively, these self-perception data indicate that, during both the Fall semester and the Spring semester, *ICB* students developed perceptions of the field of biology that more closely reflect the perceptions of professional biologists when compared with the traditional students.

ICB was intended to cultivate curiosity, and appeared to do so, based on a number of student comments expressing satisfaction with the approach. Students appreciated knowing the data-driven answers to the question "How do we know that?" for so many concepts that they would traditionally be asked to accept on faith (belief in the absence of evidence). The authors of *ICB* wanted students to develop a more realistic perspective on biology and biologists. Instead of reading and memorizing summaries of research, *ICB* readers were encouraged to take the same intellectual steps as the original scientists and draw their own conclusions. Biological knowledge does not magically appear in a textbook out of thin air; it was established by hardworking people through the scientific process, and the ICB students engaged with that process.

Furthermore, interpreting original data has the effect of humanizing biology and making it more relevant to students. These benefits were borne out by the perceptions survey data (Tables 1–3) and in student comments (Table 4), particularly the satisfaction of knowing experimental underpinnings and appreciating the constructivist learning model in general. The humanizing of science and students' understanding that people like themselves personally conducted research to discover and develop the concepts in their introductory courses can be important for increasing diversity in science. With such role models, students who have traditionally felt excluded by the scientific enterprise suddenly find biology to be a deeply personal endeavor that can certainly include them (Tsui, 2007; Chamany *et al.*, 2008).

This formative study does not represent the last improvement in Biology 111—it is the first step of many. Building on the successful use of *ICB*, C.J.P. developed the Biology 112 (macroscopic) semester using the *ICB* approach and taught it for the first time in Spring 2012. Taking the full intent of *ICB* a step further, A.M.C. and C.J.P. are team-teaching a two-semester introductory biology sequence during the 2012–2013 academic year that integrates the "small biology" and "big biology" scale for each of the five "big ideas." This new, yearlong course, Biology 113 and 114, will sequentially span all 25 chapters of the *ICB* textbook in order and will demonstrate to students the size-independent nature of biology's big ideas. Along with this new course, the two instructors will employ new labs that allow students to further explore the big ideas across the size scales. These labs are inquiry-based and guide students through student-led discovery of key concepts and skills. Students will develop their own hypotheses and design their own experiments to produce, analyze, and interpret their own original data. In addition, the *ICB* authors have sent sample chapters to colleagues at many different colleges and universities to gather student and faculty feedback. These reviews will be incorporated into the *ICB* manuscript for publication in the near future.

In conclusion, the *ICB* textbook enhances student gains in key biology competencies that most educators agree are critically important, without sacrificing content knowledge (AAAS, 2011). *ICB* students also developed a more realistic and nuanced view of their own abilities and of the discipline of biology, while making meaningful connections between seemingly disparate ideas and transferring their critical thinking gains to other courses. We predict that the faculty testing sample chapters will find *ICB* to be more rewarding than a traditional textbook. *ICB* facilitates guiding students through the data analysis and interpretation, an approach that we suspect most instructors will prefer to speeding through encyclopedic volumes of facts. *ICB* encourages the kind of thinking and learning that biology faculty engage in regularly when conducting research and may attract and nurture the next generation of scholars. A large body of literature supports the use of both active-learning techniques and constructivist approaches in science courses (reviewed in AAAS, 2011). *ICB* achieved the reported learning gains in this study without the use of active-learning methods. The only difference between the two student populations in this study was the way content was presented in the text and lectures and the extent to which critical thinking and knowledge construction were required. Presumably, even greater learning gains could be achieved with the inclusion of active-learning approaches used in conjunction with the *ICB* textbook.

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