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Article

Information Fluency for Undergraduate Biology Majors: Applications of Inquiry-based Learning in a Developmental Biology Course

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Many initiatives for the improvement of undergraduate science education call for inquiry-based learning that emphasizes investigative projects and reading of the primary literature. These approaches give students an understanding of science as a process and help them integrate content presented in courses. At the same time, general initiatives to promote information fluency are being promoted on many college and university campuses. Information fluency refers to discipline-specific processing of information, and it involves integration of gathered information with specific ideas to form logical conclusions. We have implemented the use of inquiry-based learning to enhance and study discipline-specific information fluency skills in an upper-level undergraduate Developmental Biology course. In this study, an information literacy tutorial and a set of linked assignments using primary literature analysis were integrated with two inquiry-based laboratory research projects. Quantitaitve analysis of student responses suggests that the abilities of students to identify and apply valid sources of information were enhanced. Qualitative assessment revealed a set of patterns by which students gather and apply information. Self-assessment responses indicated that students recognized the impact of the assignments on their abilities to gather and apply information and that they were more confident about these abilities for future biology courses and beyond.

INTRODUCTION

A major challenge in the teaching and learning of biology is the development of students' abilities to gather, analyze, apply, and synthesize information. These skills are important for students to understand the underlying evidence that supports basic biological concepts and the scientific process. This is particularly important in a fast-moving field, such as developmental biology, which has a very rapid rate of new information production. The specific types of skills necessary depend on the type of information involved. Novel information that is gained through experimentation and analysis of results requires skills in experimental design and technical performance. The ability to locate, use, and evaluate already available information requires information literacy skills (Porter, 2005). Although the actual skills are quite different, the general critical thinking involved is overlapping and is, in fact, interdependent (Lindquester *et al.*, 2005). Several approaches, including inquiry-based learning, reading of the primary literature, and information literacy instruction have been used by teachers to try to enhance these "process skills" in their students (DebBurman, 2002; Lindquester *et al.*, 2005).

Inquiry-based learning is a member of a larger pedagogy family that focuses on student engagement with problems, activities, and each other (McNeal and D'Avanzo, 1997; Schulman, 2004). Such approaches to teaching and learning lead to better student understanding, performance, reflection, generativity, and commitment (Schulman, 2004). Inquiry-based learning mirrors the scientific process (DiPasquale *et al.*, 2003; Handelsman *et al.*, 2004), and it has been strongly encouraged by national science commissions and granting agencies (National Science Foundation, 1996; National Research Council, 2001, 2003). In the classroom, inquiry-based learning can include student-led teaching, problem solving, and group discussions, whereas in the teaching laboratory, investigative projects in which students

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design experiments and gather their own data are the primary models (Glasson and McKenzie, 1998; Springer *et al*., 1999; DebBurman, 2002; Odom and Grossel, 2002). When students are actively involved in the process of learning they gain an increased sense of ownership, intensity, and performance (McNeal and D'Avanzo, 1997; Kolkhorst *et al*., 2001). Overall, inquiry-based learning leads to an increased understanding of the scientific process (Handelsman *et al*., 2004).

Reading of primary research papers has also been shown to be an effective pedagogical tool for the development of scientific process skills (Muench, 2000; Levine, 2001; Mulnix, 2003; DebBurman, 2002; Gillen, 2006; Kozeracki *et al*., 2006). The primary literature provides great potential for beginning science students; however, it is often difficult for students to comprehend and it is interpreted as too challenging for undergraduates by both students and faculty (Muench, 2000; Smith, 2001; Porter, 2005). It has been shown that in reading and analyzing such articles students realize how scientists develop and answer questions with specific approaches and methods and gain self-confidence in their abilities to think scientifically (Mulnix, 2003). They begin to understand that research is not done independently, but rather that individual results and observations are interwoven into a larger body of work that constitutes basic understandings in a field. It has been suggested that this not only allows students to understand how science is conducted but also enhances their understanding of basic scientific knowledge and scientific literacy (Houde, 2000; Kozeracki *et al*., 2006).

Information competency, literacy, and fluency all refer to the process of accessing and applying information appropriately. Although used somewhat interchangeably, these terms seem to emphasize different levels of information processing. Information competency often begins with the ability to define or recognize a research need (Curzon, 1998), whereas information literacy focuses on the ability to use appropriate technologies to access specific information (American Library Association [ALA], 2004). The ALA suggests that "Information literacy forms the basis for lifelong learning. It is common to all disciplines, to all learning environments, and to all levels of education" (ALA, 2004). Many information literacy initiatives focus on general skills for information searching and evaluation. Grafstein (2002) and Smith (2003) present arguments for discipline-specific information literacy skills, particularly for the development of higher-level concepts and applications (Smith, 2003). Information fluency pertains to this level of information processing by emphasizing the evaluation and application of specific information. The information-fluent student demonstrates the ability to collect information and critically analyze sources to formulate logical conclusions (Associated Colleges of the South, 2002). Building on the foundation of basic information literacy, more emphasis is currently being placed on the development of subject-specific skills. In 2006, ALA developed and released the *Information Literacy Standards for Science and Engineering/Technology*. One of the primary assertions of the document is that "[s]cience, engineering and technology disciplines require that students demonstrate a competency not only in written assignments and research papers but also in unique areas such as experimentation, laboratory research, and mechanical drawing" (ALA, 2006).

Currently, much of the literature pertaining to information skills for biology students tends to focus on introductory-level courses (Mulnix, 2003; Lindquester *et al*., 2005). Porter (2005) has described a series of assignments that he has used to develop information literacy skills (information fluency) in his Advanced Cell Biology course. These assignments focus on the reading and analysis of primary literature along with the writing of abstracts and a position paper based on primary research articles. He found that through these assignments, upper-level students enhanced their abilities to process complex information.

In past iterations of an upper-level Developmental Biology course at Connecticut College, students have regularly read and critiqued research articles. Students in the course have searched the primary literature for articles related to investigative projects that they design in the course-associated laboratory. Although this course design did give students some exposure to searching for and using information sources, they often had difficulties finding appropriate articles, understanding the articles, and most importantly, integrating their own findings with published results. These particular abilities, which we refer to as discipline-specific information literacy skills or information fluency skills, are of benefit to all students, but they are particularly important for those who will go on to graduate or medical school. To more intentionally develop such discipline-specific information fluency skills, we developed a tutorial followed by a set of linked assignments that lead students through different levels of information gathering and processing. The experiences included 1) a tutorial on database searches and literature, 2) discussion and analysis of individual figures and conclusions from primary research articles, and 3) progressive writing assignments based on investigative laboratory projects. Quantitative assessment from our study suggests that intentional assignments such as those described here lead to enhanced information fluency. A qualitative assessment of students' experiences during the semester reveals a set of common patterns of how they gather and apply information.

PEDAGOGICAL DESIGN

Overview of the Course

This study was performed over two semesters in a small upper-level Developmental Biology course at Connecticut College. The course met twice a week for 3 h each, with flexible time in the classroom and the laboratory. There were seven students in the course the first semester and 11 students the second semester. The majority of the students had taken core introductory courses, Organisms, Cells, and Genetics. Several students had independent research experience. The course objectives were to introduce students to the many exciting facets of developmental biology, to engage them in the experimental approaches used to study a variety of developmental processes in different organisms, to develop their abilities to design experiments and analyze results, to enhance their writing and critical-thinking skills, to enhance their information literacy skills, and to promote their thinking about the social issues related to the field of developmental biology.

Student Experiences and Assignments Related to Information Fluency

Early in the semester, students were guided through a discipline-specific tutorial for online searching of journal databases, which focused on how to assess the quality and appropriateness of a particular journal article. This included a presentation on the difference between scholarly (subscription) databases and information found on the open Web. The importance of critical evaluation of websites and journals and the difference between primary and secondary sources was also discussed. Each student was logged on to an individual computer and participated in searches of science-specific databases related to developmental biology, including PubMed, Science Direct, and Web of Science.

Students pursued a 3-wk-long investigative lab project early in the semester and later pursued a second investigative lab project over a 5-wk period. Six linked assignments focused on building information fluency skills were given throughout the semester (Box 1). Assignments 1 and 6 were similar, and they were used as a pretest and a posttest for assessment purposes. Responses to each assignment were graded, returned, and discussed with the student before the next assignment was given.

Box 1. Set of Linked Assignments Designed to Intentionally Enhance Information Fluency Skills

Assignment 1: Where is *Sonic hedgehog* transcribed during *Xenopus* development?[a] Search for and obtain a figure within a primary research article that addresses this question. Analyze the data and write one paragraph that describes how this figure answers the question. Bring the figure to class and be ready to present your figure to the class.

Assignment 2: You and your collaborator(s) are planning to publish the results of your project. Draft an outline of the main points for the introduction to your paper in the order you plan to present them. Include a statement with your original hypothesis and attribute references (at least three primary research articles) to support your main points. Hand in copies of the primary references with the supporting evidence highlighted.

Assignment 3: Write a discussion section based on the results from your first project. Begin with a short paragraph summarizing your results. Compare your results to published findings by others. Be sure to apply your references appropriately. Hand in the papers you are referencing with appropriate text and figures highlighted. End your discussion with a paragraph on what future experiments could be done to further understanding of your question.

Assignment 4: Journal Article Critique Guidelines

- What were the major questions/hypotheses proposed in this article?
- What information (experimental evidence published in other papers) is required to support/understand this article?
- What experimental techniques were used to address these questions?
- What experimental evidence and arguments did the author(s) present? Explain the results figure by figure. Critically analyze the data and the way it is presented.
- What did the author(s) conclude? Do you agree with the author(s)' conclusions?

Critically analyze the authors' conclusions and how these conclusions fit with previous results.

Assignment 5: Write a complete scientific paper based on the results from your second independent project. Include the following sections: introduction, methods, results, discussion, references, and acknowledgements. You must use at least four primary references to support your statements.

Assignment 6: Where is *FGF10*[b] expressed during chick development? What regulates *FGF10* expression? What is the major function of *FGF10*? Search for and obtain a figure within a primary research article that addresses one of the questions above. Analyze the data and write a paragraph that describes how the data in the figure answers the question. Bring the figures to class and be ready to present them to the class.

[a] *Sonic hedgehog* is a gene that codes for a soluble signal sent from one cell to another to induce cells to specialize during development. *Xenopus* is the genus name for a type of frog commonly used to study developmental mechanisms.

[b] *FGF10* is a gene that codes for a soluble signaling protein called Fibroblast Growth Factor10.

Methodology

In this study, a quantitative approach was used to assess the effectiveness of specific assignments on information fluency skill development and a qualitative approach to determine how students access and apply information. Analysis of students' written answers to assignments and student self-assessment evaluations were used to quantify the impact of the intentional assignments. Specific assessment of students' integration of information into project-related papers was done only for the fall 2004 course. Focus group interviews done by the instructor, student self-assessment evaluations, and analysis of students' writing by the instructor were used to identify general patterns in the students' approaches to gathering and applying information. The importance of multiple assessment measures has been described for science pedagogy studies (Siebert and McIntosh, 2001; Dancy and Beichner, 2002; Sundberg, 2002). Sundberg (2002) suggests that "Quantitative assessment provides the broad strokes; qualitative assessment fills in the details. Both are needed to produce a good picture of student learning." Dancy and Beichner (2002) support both as well: "We cannot emphasize enough: the best research designs employ both methods."

This study focused on a specific parameter to assess whether students used direct or indirect information to support their statements or address specific questions. We define direct information as that which directly involves the object (gene or molecule in this case) or process being examined and indirect information as that which is related to the object or process being examined. A general example of this analysis can be demonstrated by answers to the question: Where is Connecticut College? A direct answer would be the campus address supported with a map of the New London area and the campus identified. An indirect answer would be the address of the Connecticut College president's house supported with a photo of him, his home, or both. A molecular example of this analysis would be demonstrated by answers to the question: Where is gene A transcribed during development? A direct answer would be primary data from a figure or table showing results from a specific technique that analyzes transcription (i.e., a Northern blot or reverse transcriptase-polymerase chain reaction). An indirect answer could be a result from a technique that analyzes the function of a gene (i.e., ectopic expression or mutant studies). This answer would report information about how the gene product works, but not about where it is present. Another type of indirect answer would be a review article that describes transcription results but that does not provide primary data. Students' written answers to specific questions and integration of information within their writing of introduction and discussion sections of a scientific paper were evaluated to determine whether they consistently applied direct or indirect information.

Overall class performance for specific assignments was used to quantify the impact of specific assignments on information processing, whereas evaluation of an individual student's work was used as an assessment of the progress of skill building. At the end of the semester, a survey was given to students to provide an opportunity for self-assessment of the impact of the assignments on information fluency skill development.

RESULTS AND DISCUSSION

Development of Information Fluency Skills through Assignments Linked to Inquiry-based Laboratory Projects

Students pursued two multiweek investigative research projects in the laboratory during the semester. Laboratory and class time was devoted to hypothesis development and experimental design. Students performed database literature searches in the laboratory to identify previously published research on the investigative research projects that they pursued. Each lab group discussed their ideas and primary literature sources with the course instructor (Eastman) before writing their hypotheses and performing the experiments. The initial projects focused on sea urchins, planaria, and various angiosperms. The second projects included flies, chicks, zebrafish, and *Arabidopsis* (Supplemental Material 1, lab syllabus).

To build foundational information literacy skills, students were given a tutorial by one of us (Gehring) early in the semester just as they were beginning their projects. They were then given a specific assignment pertaining to their laboratory project. They were asked to further search and read articles (review and primary research articles) on their own that addressed the projects they proposed and to write an introduction section of a paper with this information (Box 1, assignment 2). They were instructed to include at least three primary references and to highlight the information from the published research that they applied in their paper.

Introduction sections from students in the fall 2004 semester were analyzed. The majority of students provided at least three primary references in their introductions; however, several used review articles. This suggests that some students were still not clear on the difference between primary research and review articles. Only four of seven students (57%) accurately applied references that provided direct information (see Table 3, individual assessment of assignment 2). Several students used information they found within the abstract rather than within the actual article. In a focused interview with these students, it was clear that they had not actually read any of the articles, rather they had identified and used information from the abstract. After returning student papers, the instructor (Eastman) provided specific examples of direct and indirect information. We also discussed the purpose of abstracts as introductory information that can help decide whether an article is appropriate and the importance of actually reading the entire article, especially the pertinent data figures, before using it as a source.

Students were given a second assignment pertaining to the same inquiry-based laboratory project. They were asked to write a discussion based on the results from their project and to compare their results with published findings (Box 1, assignment 3). All students applied at least three references. Analysis of student papers from fall 2004 showed that five of seven students (71%) accurately applied references that provided direct information. These data demonstrate that the assignments along with follow-up discussions were effective in improving most students' abilities to apply appropriate articles. However, almost one-quarter of the students were still unable to identify direct information.

Students pursued a second independent laboratory project that they designed and implemented during the last 5 wk of the semester. They again searched the primary literature to develop their hypothesis/question and to determine appropriate methods. After performing the experiments and analyzing results they wrote a complete scientific paper based on their findings (Box 1, assignment 5; and Table 1). In the introduction and discussion, they were required to reference at least four primary research articles. All of the students used at least four primary research articles, and five of six students (83%) accurately applied information. This suggests that intentional assignments linked to investigative projects may improve students' abilities to gather and apply information.

Primary Research Article Discussions

To reinforce the understanding of how specific information from a primary research article directly or indirectly answers a question, four different articles were assigned throughout the semester. Students were given guidelines for a critique (Box 2), and a group discussion was focused on these guidelines. For the first article discussion, students were simply asked to read the articles. Although several students came very prepared for the discussion, the majority of students had either not read the paper or had not engaged it seriously. For subsequent discussions, a written critique was due the day of the discussion, and students were able to

Table 1. Titles of inquiry-based projects in developmental biology: fall 2004 and 2005

Project title
Examination of the role of calcium during early sea urchin fertilization: effects of a calcium ionophore and a calcium chelator
Effects of the mitogen-activated protein (MAP) kinase inhibitor U0126 on primary mesenchymal cell migration in sea urchins
Tracking of neoblasts with 5-bromo-2′-deoxyuridine labeling during planaria regeneration
Real-time RT-PCR detection of zebrafish cyclin E expression during the mid-blastula transition
Lithium affects the expression of glycogen synthase kinase-3β in *Drosophila* embryos
Retinoic acid affects the transcription of the *HoxB-8* gene in early chick development
Detection of ethanol induced changes in gene expression during *Drosophila* development using RT-PCR
Where is Leafy expressed?: RT-PCR analysis in *Arabidopsis* meristems
Where is PAX6 expressed?: RT-PCR analysis during zebrafish development

refer to their critiques during the discussion. Students answered the critique questions in a circular manner (Figure 1). In turn, each student was asked to contribute an answer to the question being discussed. The results section was discussed figure by figure, and students were expected to be able to explain the details of the results (including controls) and the take-home message. To decrease fear levels, students were allowed to pass twice on answering a question, but they were usually very reluctant to do so. This approach to discussing the article kept students engaged and ensured that all students stayed involved in the discussion. Before the discussion of each article, students were asked to reflect on their experiences while reading article. They reported initial discomfort and even fear in reading the first article; however, they became progressively more comfortable with each additional article they read. The discussions became progressively more relaxed, and student engagement with the details of the data and conclusions became more intense with each additional article we discussed.

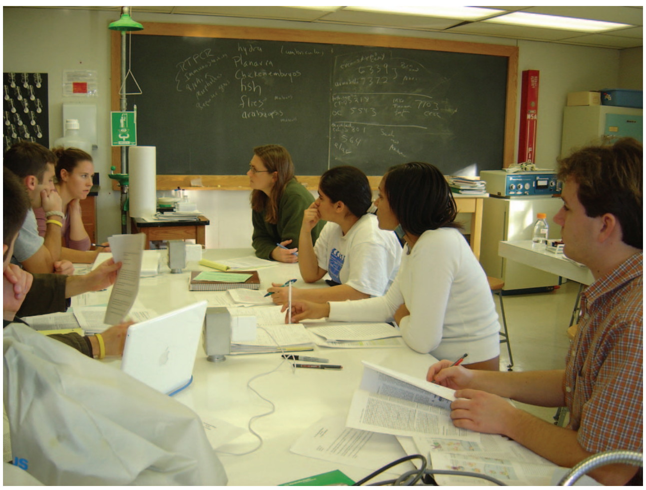

Figure 1. Students engaged in a "circular discussion" of a journal article in the developmental biology laboratory. Students sat in a circle around a laboratory table and answered critique questions in turn.

Box 2. Developmental Biology (Bio302) Critique Guidelines

What are the major questions/hypotheses proposed in this article?

What background information (experimental evidence published in other papers) is required to support/understand this article?

What experimental techniques were used to address these questions?

What experimental evidence and arguments did the author(s) present? Explain the results figure by figure. Critically analyze the data and the way it is presented.

What did the author(s) conclude? Do you agree with the author(s)' conclusions?

Critically analyze the author's conclusions and how these conclusions fit with previous results.

Identification and Application of Direct Information: Pretest and Posttest

Pretest and posttest assignments were used to determine the effectiveness of the journal article discussions, and they linked assignments on students' abilities to identify and apply appropriate information. The pretest was given early in the semester, and a posttest was given at the end of the semester. These assignments asked similar questions pertaining to the topic of transcriptional regulation during development. Before the pretest assignment, the mechanisms and techniques for studying transcription and transcriptional regulation, including Northern blots, in situ hybridizations, reverse transcriptase-polymerase chain reaction (RT-PCR), and reporter genes, were presented and discussed with the class. All of the students were able to locate a research article containing information about Sonic hedgehog (Hh) during *Xenopus* development. However, only 27% of the students provided data and figures that directly answered the question (Figure 2). Examples of direct information included results from RT-PCR and in situ hybridization experiments, whereas indirect information included phenotypes of Sonic hedgehog pathway mutants and Sonic Hedgehog overexpression. At least three papers that contained appropriate direct information and 15 papers that contained indirect information were available to the students online.

After students presented their figures, the class discussed how each of the figures or results answered the question. Students analyzed one another's answers to determine whether they provided direct or indirect information about hedgehog transcription. This allowed the assignment to be a learning tool and a pretest tool.

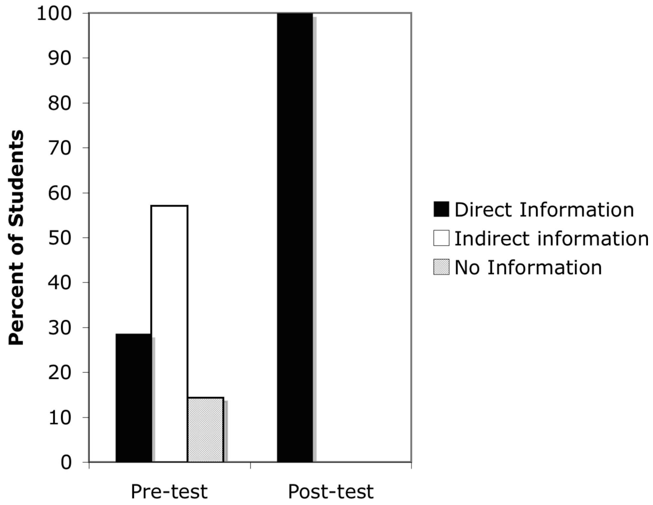

Figure 2. Comparison of information application in pretest and posttest answers. Students were given a pretest at the beginning of the semester and a posttest at the end of the semester to assess progress in their abilities to apply direct information from a primary research article. The pretest question was, Where is Sonic hedgehog transcribed during *Xenopus* development? The posttest question was, Where is *FGF10* expressed during chick development?

At the end of the semester, students were given a specific question pertaining to the topic being discussed in class, fibroblast growth factor (FGF) signaling during vertebrate development. Similar to the pretest assignment, they were asked to find a figure within a paper that addressed the question and to analyze the data. Then they explained (written and orally) their analysis and how the data from the figure answered the question, just as they did for assignment 1. At least four papers that provided direct information and 11 papers that provided indirect information were available online to the students. Because the number and proportion of direct to indirect papers available to the students were not significantly different between assignments 1 and 6, they were used as pretest and posttest tools. All students identified and presented data from primary research articles that directly supported the questions in the assignment. Results from this assignment were compared with those observed for assignment 1 (Figure 2). Results from this assessment suggest that the linked set of assignments presented here provide a learning experience that successfully builds students' information fluency skills.

Assessment of Information Fluency Skill Development in an Individual Student

Because analysis of students' responses to the linked assignments revealed a general trend of improvement, we sought to gain another perspective through the assessment of the progress of an individual student through the six assignments. A preliminary analysis of all students' progress through the assignments was done, and an individual student's work presented in this analysis was chosen to illustrate an example of progressive improvement because the student did not provide direct information in assignment 1. The progress made by this student is representative of the majority of the students. Three parameters for each of the assignments were analyzed: 1) whether a valid source was used (i.e., a primary research article), 2) whether direct information was presented, and 3) how the student integrated the information into a written document (Supplemental Material 2). This assessment of an individual student's progressive development of information fluency skills provides further insight into the effectiveness of specific assignments (Table 2). In assignment 1 (pretest), the student did not provide direct information. Although the answer includes information about the Hh signaling pathway and specifically refers to its function during *Xenopus* development, it does not directly address the question of where Hh is transcribed. The student did provide direct information in assignment 2; however, the information was not integrated in assignment 2 appropriately. This suggests that assignment 1 provided a successful learning experience for understanding direct information; however, the student was unable to apply and synthesize the information. This higher-order level of thinking (Allen and Tanner, 2002) was eventually mastered, because the student accurately applied direct information in assignments 3 and 5. This individual assessment mirrors the group results and suggests a progressively deeper understanding of information gathering and application as students worked through the set of assignments.

Patterns in Development of Information Fluency Skills

Qualitative analysis of student responses and experiences was focused on how they were answering the questions, how they were experiencing their projects and assignments, and the patterns that were emerging from studying their responses. A set of patterns was identified as students developed their information fluency skills (Table 3). Evaluation of assignments revealed a lack of clarity on different types of scientific articles. Student understanding of the differences between review articles, opinion essays, and primary journal articles improved after the library tutorial. This assessment also showed that student confusion about how to identify information within a journal article and to directly apply the information was apparent in early assignments. In addition, many students were unclear about how to integrate their experimental findings with those in the literature. The use of focus group interviews done by the instructor allowed the identification of a different set of patterns. These included the lack of understanding about the importance of reading data within a source article and not just relying on information in the abstract. Students were also unclear about the dependence of basic "textbook" concepts on primary data.

Finally, students who had pursued research projects during the summer, as independent studies projects, or both, came into the course with better information fluency skills. These interviews also revealed that students were intimidated by the language and different writing style in primary research articles.

Table 2. Assessment of an individual student's progress in information fluency

Assignment no.	Assessment parameter		
	Use of valid source[a]	Direct information[b]	Integration of information[c]
1	The student used a valid source, Zhang *et al*. (2001), and identified a specific figure to answer the question.	Indirect information was presented. Specifically, the student attempted to answer the question of where Hedgehog is transcribed during *Xenopus* development by describing the mutant phenotype of the receptor for Hedgehog. "Through this mutation with smoM2 it can be concluded that the undisrupted Hh pathway is transcribed in the eye, coelomic body wall and the gut during *Xenopus* development."	
2	The student used a valid source, Kumano *et al*. (2001), and identified specific information within the article.	Direct information was presented. The student's project focused on the use of a specific inhibitor, U1026, to identify a role for MAP kinase signaling during early embryonic development in sea urchins. The student highlighted a specific figure and accompanying text: "In order to compare MEK inactivation with MAP kinase inactivation, unfertilized sea urchin eggs were incubated in 0.5 μM U1026 for various times and then MAP kinase activity was assessed by immunoblotting with the phospho-MAP kinase antibody (Fig. 5A). After 20 min of exposure to U1026, MAP kinase activity was substantially decreased (Fig. 5, left).	The information directly supported the statement made in the student's introduction; however, the student did not explain how this information specifically related to the hypothesis addressed in the student's project. "It has also been shown that compound U0126 will act as an inhibitor of the MEK signaling pathway (Kumano *et al*., 2001)."
3	The student used a valid source, Fernandez-Serra *et al*. (2004), and identified specific information within the article.	Direct information was presented. One example: "Control gastrulae show normal gastrulation, while treated gastrulae lack most mesenchyme cells and gut invagination (Fernandez, 2004)."	The student saw no effect of U0126 on early sea urchin development. The identified information is appropriate; however, in the integration of the information the student inappropriately referred to the specific figures and tables, making it unclear which information was from the student's project and which was from the published article: "If the inhibition of primary mesenchymal cell ingression was achieved by U1026 then the results would have been different than observed. Effects of successful mesenchymal ingression can be seen in fig. 3 and table 1 (Fernandez, 2004). With the treatment of U1026 primary mesenchymal cell ingression is greatly altered and disturbed."
5	The student used valid sources throughout the paper.	Direct information was presented. One example: "Recent research has found that the mutant *cheapdate*, an allele of *amnesiac*, shows an increased sensitivity to the exposure of ethanol (Moore *et al*., 1998)."	The student's project focused on the effects of ethanol on the expression of two genes in *Drosophila melanogaster*. Appropriate information from a valid source was integrated in the paper to support statements in the introduction and discussion. The statements and information were clearly related to the hypothesis: "A recent study has shown that mice lacking m-neul, a mouse homologue of the *Drosophila* nerualized [sic] gene exhibit hypersensitivity to ethanol (Ruan *et al*., 2001). Recent research has also found that the mutant cheapdate, an allele of amnesiac, shows an increased sensitivity to the exposure of ethanol (Moore *et al*., 1998). Both of these past reports indicate that amnesiac and neuralized are ethanol sensitive and thus it seems likely that their regulation would indeed be affected by ethanol exposure."
6	The student used a valid source, Sakiyama *et al*. (2003), and identified a specific set of data to answer the given question.	Direct information was presented. "Figure 3 shows that ectopic Tbx4 induces ectopic FGF10 expression."	

[a] Use of a valid source refers to the type of article used by the student. Primary research articles are valid sources in this case, whereas websites or review articles are invalid.

[b] Direct information refers to the type of experiments and results presented in the primary research article. The student used direct information when the article referenced contained results that directly supported statements made by the student. (See Methodology in text for a definition of direct vs. indirect information.)

[c] Integration of information refers to how the student used the specific source. Successful integration occurred when the student used the information to support statements in the introduction and discussion sections (assignments 2, 3, and 5) and made connections between the inquiry-based project and the paper referenced.

Table 3. Class evaluation of information fluency skills (n = 14)

Outcome	Mean score[a]	SD
Assignments 1 and 6 enhanced your ability to identify appropriate information to directly answer a question	4.00	1.00
Assignments/activities enhanced your skills in searching the primary literature	4.14	1.46
Assignments 2 and 3 enhanced your ability to support your written statements with evidence from the primary literature	3.71	1.22
Assignments developed your general skills in information gathering	4.14	1.25
Journal article discussion and written critiques enhanced your ability to analyze data	4.57	1.12
Journal article discussion and critiques enhanced your understanding of concepts in developmental biology	3.13	0.91

[a] Survey answers were on a scale of 1–5: greatly enhanced (5), somewhat enhanced (3), and not enhanced (1).

Table 4. Identification of patterns in students' information fluency skills

Assessment tool	Common patterns identified across students
Evaluation of assignments	
	Lack of clarity on different types of scientific articles
	Confusion between direct and indirect information
	Lack of clarity on how to integrate novel results with published results
Focus group interviews	
	Research experiences enhance information fluency skills
	Use of information from an abstract rather than actual data within the article
	Intimidation by information and jargon in primary research articles
	Lack of understanding of link between primary data and basic concepts
	Use of information from another source paraphrased in introduction or discussion of cited article

Student Self-Assessment of Information Fluency Skills

At the end of the semester, an anonymous student evaluation of the assignments and the students' sense of how the assignments impacted their information literacy skills was solicited. Fourteen of the 18 students responded to the evaluation. In addition to rating their feelings about the effectiveness of the assignments, students also had the opportunity to explain how the assignments impacted their learning.

Overall, students were positive about the impact of the assignments on their information literacy and data analysis skills (Table 4). Interestingly, student perceptions were less positive about assignments 2 and 3 (introduction and discussion sections based on their first investigative projects), even though our assessment of subsequent assignments showed improvement in their application of direct information. Students who responded that their skills were "somewhat" enhanced commented that "they also helped when writing the final exam" and "not as much as the final paper, but somewhat." One student stated that "all of these assignments required me to support my statements and thus I improved as the semester went on." Another student stated that "Assignments 2 and 3 as well as the final paper forced me to utilize the online databases, a skill that proved invaluable in other classes. I also was forced to truly understand what the papers were trying to get across because I then had to apply that to my own paper." Almost all the students felt that the journal article discussion did not greatly enhance their understanding of course material. This is not necessarily surprising, because information in research articles is often very specialized and left open-ended, whereas information in textbooks (which is what students are most used to in science courses) generalizes, clarifies, and "tidies up" the information. DebBurman (2002) reported that students in an Introductory Cell Biology course favorably rated journal article discussions as relevant to their understanding of course content. It is possible that the difference in course level and the choice of primary journal article could affect students' perceptions about its relevance to course content. Interestingly, students in the same study did not find an assignment in which a lab report was written as a primary article relevant to their learning course content (DebBurman, 2002). These findings, along with ours, suggest that analysis of primary literature does not necessarily enhance learning of course content, but rather it clarifies the understanding of how the process of science is done.

CONCLUSIONS

This study on the integration of inquiry-based learning with information literacy skill building suggests that intentional assignments using primary literature analysis and investigative projects are useful for the development of information fluency. Results from the study also reveal patterns as to how students gather and apply information. Self-assessment responses indicate that students recognize the impact of the assignments on their abilities to process information and that they feel more confident about these abilities for future biology courses and beyond. Intense discussion and analysis of primary data along with the application of published data in students' introduction and discussion sections enhanced students' abilities to better identify and integrate appropriate information. This ability to integrate novel results with published results is obviously an important skill for students who plan to pursue graduate work in the sciences. It requires critical thinking that can be applied to other disciplines as well. Although this set of assignments was designed for a small, upper-level Developmental Biology course within a liberal arts curriculum, modifications of the individual assignments described here could be made to allow them to be used in larger or more introductory courses on any scientific topic. Our study suggests that an intentional tutorial focused on discovery and critical use of scholarly sources followed by a focused information-processing task (assignments 1 and 6) and a writing assignment related to a short independent project (assignments 2 and 3) are the most important aspects of the information fluency curriculum we have developed. Expansion of some of the assignments could lead to further tools for teaching information fluency skills. Implementation of all the assignments presented here would be difficult in a large class; however, the use of several of these most important assignments may be feasible. Alternatively, individual assignments could be modified and used individually. For example, a pool of matched questions similar to assignments 1 and 6 could be developed so that students could work individually and then share with one another to hone their abilities to identify and apply direct information. The information fluency skills that students develop through these assignments will not only aid them in other courses but also give them a firm foundation for and confidence in accessing and applying information as life-long learners.

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REFERENCES

Allen, D., and Tanner, K. (2002). Approaches to cell biology teaching: questions about questions. Cell Biol. Educ. *1*, 63–67.

American Library Association (2004). Information Literacy Competency Standards for Higher Education. http://www.ala.org/acrl/ilcomstan.html (accessed 1 March 2005).

Associated Colleges of the South (2002). ACS IF definition. http://www.colleges.org/~if/if_definition.html (accessed 1 March 2005).

Curzon, S. (1998). Information Competence Memorandum. http://library.csun.edu/susan.curzon/infoprop.html (accessed 15 March 2006).

Dancy, M. H., and Beichner, R. J. (2002). But are they learning? Getting started in classroom evaluation. Cell Biol. Educ. *1*, 87–94.

DebBurman, S. K. (2002). Learning how scientists work: experiential research projects to promote cell biology learning and scientific process skills. Cell Biol. Educ. *1*, 154–172.

DiPasquale, D., Mason, C., and Kolkhorst, F. (2003). Exercise in inquiry: critical thinking in an inquiry-based exercise physiology laboratory course. J. Coll. Sci. Teach. *32*, 388–393.

Fernandez-Serra, M., Consales, C., Livigini, A., and Arnone, M. I. (2004). Role of the ERK-mediated signaling pathway in mesenchyme formation and differentiation in the sea urchin embryo. Dev. Biol. *15*, 384–402.

Gillen, C. M. (2006). Criticism and interpretation: teaching the persuasive aspects of research articles. CBE Life Sci. Educ. *5*, 34–38.

Glasson, G. E., and McKenzie, W. L. (1998). Investigative learning in undergraduate freshman biology laboratories. J. Coll. Sci. Teach. *27*, 189–193.

Grafstein, A. (2002). A discipline-based approach to information literacy. J. Acad. Libr. *28*, 197–204.

Handelsman, J. *et al*. (2004). Education. Scientific teaching. Science *304*, 521–522.

Houde, A. E. (2000). Student symposia on primary research articles: a window into the world of scientific research. J. Coll. Sci. Teach. *28*, 252–253.

Kolkhorst, F. W., Mason, C. L., DiPasquale, D. M., Patterson, P., and Buono, M. J. (2001). An inquiry-based learning model for an exercise physiology laboratory course. Adv. Physiol. Educ. *25*, 117–122.

Kozeracki, C. A., Carey, M. F., Colicelli, J., Levis-Fitzgerald, M., and Grossel, M. (2006). An intensive primary-literature-based teaching program directly benefits undergraduate science majors and facilitates their transition to doctoral programs. CBE Life Sci. Educ. *5*, 340–347.

Kumano, M., Carroll, D. J., Denu, J. M., and Foltz, K. R. (2001). Calcium-mediated inactivation of the MAP kinase pathway in sea urchin eggs at fertilization. Dev. Biol. *236*, 244–257.

Levine, E. (2001). Reading your way to scientific literacy. J. Coll. Sci. Teach. *31*, 122–125.

Lindquester, G. J., Burks, R. L., and Jaslow, C. R. (2005). Developing information fluency in introductory biology students in the context of an investigative laboratory. Cell Biol. Educ. *4*, 58–96.

McNeal, A. P., and D'Avanzo, C. (1997). Student-Active Science: Models of Innovation in College Science Teaching, Orlando, FL: Saunders College Publishing.

Moore, M. S., DeZazzo, J., Luk, A. Y., Tully, T., Singh, C. M., and Heberlein, U. (1998). Ethanol intoxication in *Drosophila*: genetic and pharmacological evidence for regulation by the camp signaling pathway. Cell *93*, 997–1007.

Muench, S. B. (2000). Choosing primary literature in biology to achieve specific educational goals. J. Coll. Sci. Teach. *29*, 255–260.

Mulnix, A. B. (2003). Investigations of protein structure and function using the scientific literature: an assignment for an undergraduate cell physiology course. Cell Biol. Educ. *2*, 248–255.

National Research Council (2001). Science Teaching Reconsidered, Washington, DC: National Academy of Sciences Press.

National Research Council (2003). BIO 2010, Transforming Undergraduate Education for Future Research Biologists, Washington, DC: National Academy of Sciences Press.

National Science Foundation (1996). Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering and Technology, Arlington, VA: National Science Foundation.

Odom, D. P., and Grossel, M. J. (2002). Using the two-hybrid screen in the classroom laboratory. Cell Biol. Educ. *1*, 43–62.

Porter, J. R. (2005). Information literacy in biology education: an example from an advanced cell biology course. Cell Biol. Educ. *4*, 335–343.

Ruan, Y., Tecott, L., Jiang, M. M., Jan, L. Y., and Jan, Y. N. (2001). Ethanol hypersensitivity and olfactory discrimination defect in mice lacking a homolog of *Drosophila* neuralized. Proc. Natl. Acad. Sci. USA *93*, 99-7-9912.

Sakiyama, J., Yamagishi, A., and Kuroiwa, A. (2003). Tbxr-Fgf10 system controls lung bud formation during chicken embryonic development. Development *130*, 1225–1234.

Schulman, L. S. (2004). The Wisdom of Practice: Essays on Teaching, Learning, and Learning to Teach, San Francisco, CA: Jossey-Bass.

Siebert, E. D., and McIntosh, W. J. (2001). College Pathways to the Science Education Standards, Arlington, VA: NSTA Press.

Smith, E. (2003). Developing an Information Skills Curriculum for the Sciences. Issues Sci. Technol. Libr. *37*.

Smith, G. R. (2001). Guided literature explorations. J. Coll. Sci. Teach. *30*, 465–469.

Springer, L., Stanne, M. E., and Donovan, S. S. (1999). Effects of small-group learning on undergraduates in science, mathematics, engineering, and technology: a meta-analysis. Rev. Educ. Res. *69*, 21–51.

Sundberg, M. D. (2002). Assessing student learning. Cell Biol. Educ. *1*, 11–15.

Zhang, J., Rosenthal, A., deSauvage, F. J., Shivdasani, R. A. (2001). Downregulation of Hedgehog signaling is required for organogenesis of the small intestine in *Xenopus*. Dev. Biol. *229*, 188–202.