Research Article

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The Five Core Concepts of Biology as a Framework for Promoting Expert-Like Behaviors in Undergraduates Learning How to Read Primary Scientific Literature

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A growing body of literature shows that primary scientific literature (PSL) is a valuable and useful tool for science, technology, engineering, and math education. We currently have a relatively limited understanding of how skills relating to reading PSL progress through academic careers, i.e., the process by which expertise in reading PSL develops. In this study, we built on previous work showing clear differences in strategies that experts use to read PSL that are not often available to or documented with novice PSL readers. Using the five core concepts (5CCs) of biology, outlined in *Vision and Change in Undergraduate Biology*, as a framework for student engagement with PSL, we investigated whether the 5CCs can be used to (i) increase student engagement with PSL, (ii) provide a context for PSL, and (iii) integrate student prior knowledge when reading PSL. Second, we investigated whether a 5CCs-based, semester-long intervention could shift student reading habits to be more expert-like. As no direct assessment for this exists, we instead measured student motivation for reading PSL, their Biology identity, and their perceived learning gains in science. We found that, through the use of the 5CCs as a framework for reading PSL, students were able to integrate previous knowledge and engaged with PSL constructively. Additionally, we saw positive shifts in student motivation for reading PSL, student Biology identity, and student self-reported learning gains in Biology. Taken together, the 5CCs, as a disciplinary framework, have great potential as a pedagogical tool for increasing student engagement with PSL in Biology classrooms.

KEYWORDS 5CCs interpretation, core concepts of biology, introductory biology

INTRODUCTION

Engaging students in what it means to do research has become a key emphasis in science education. Primary scientific literature (PSL) can serve as a gateway to the research process. Through reading and deconstructing PSL, students can gain an understanding of how scientists design their experiments, analyze and draw conclusions from their data, and present their results, fundamentally allowing students to experience how researchers progress from a problem to a set of data to a new conclusion.

Educational interventions using PSL include journal clubs, data and figure exploration, tutorials on how to read PSL, tailored assignments preparing students to discuss PSL, annotated PSL, and full courses being taught only with PSL (1–13). Collectively, these interventions engage students in science process skills that are a critical part of a holistic science education. For example, closely analyzing PSL in a classroom setting can engage students in discussion and debate around interpretations of experimental data while building their insight into both the nature of science and researchers themselves (2). Teaching with PSL promotes students' critical thinking, experimental design ability, and epistemological maturation, as well as improving students' attitudes about science and scientists (3, 14–18). PSL also promotes the development of creativity through study design assignments (2, 14).

Despite the value of PSL in science, technology, engineering, and math (STEM) education, most curricula lack any formal training for undergraduates on how to critically read PSL. In addition, the readability of PSL has decreased over time, essentially making this literature inaccessible to most students (19). Furthermore, the technical nature of research articles, the mathematical or statistical tools that may have been used in data analysis, and discipline-specific jargon all serve as barriers for students trying to engage with PSL (20). Taken together, these issues create a situation where students are left

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to develop an extremely critical and challenging scientific skill mostly on their own. This in turn sets students up for a difficult future, as it has been estimated that scientists spend 23% of total work time reading PSL, with the number of PSL an individual scientist reads annually having increased from 188 to 280 between 1993 and 2005 (21–22). PSL is going to be a part of these students' academic and professional lives, and we should better prepare them to be successful.

How does expertise in reading PSL develop?

We currently have a relatively limited understanding of how skills relating to reading PSL progress through academic careers, i.e., the process by which expertise in PSL develops (23–24). Expert versus novice comparisons are valuable research tools, as they provide practical insights into how to aid novices in developing more expert-like skills (24). In general, we know that expert PSL readers value different sections of PSL than novice readers do (23–24). For example, expert PSL readers place a higher value on results and methods sections than novice readers (23). These results are in agreement with a separate study that found that undergraduate students tended to avoid figures and data, and they are also in agreement with the technical nature of PSL being a barrier to engagement (25). Overall, readers consider the abstract and introduction sections easy to read; however, undergraduate students ranked the abstract as being important, while expert readers ranked the abstract as relatively unimportant (23). Collectively, these data suggest caution in initially teaching students how to read PSL in the manner of experts, as novice readers do not yet grasp the nuances of PSL. Therefore, a PSL intervention that shifts away from the procedural learning of PSL may be a more constructive introduction to PSL.

Engaging students with PSL

An alternative to procedural learning could be to focus on engaging students constructively. The ICAP (interactive, constructive, active, and passive) framework can be used for investigating levels of student cognitive engagement during tasks through specific observable behaviors (24, 26, 27). The ICAP hypothesis divides active learning into four hierarchical modes: (1) passive, or receiving; (2) active, or manipulating; (3) constructive, or generating; and (4) interactive, or dialoguing (27). When engaging with PSL, students who simply read the paper would be considered passive (mode 1); students who engage in actions such as annotating the text would be considered active (mode 2); students who generate notes and/or summaries in their own words would be considered constructive (mode 3); and students who debate the content and/or findings of PSL with others would be considered interactive (mode 4) (24). Expert PSL readers were found to engage with PSL at a constructive level (mode 3) more often than students (24). Therefore, a more effective pathway to teaching students the "bigger picture" of PSL could be to focus more specifically on how students engage with PSL and to develop interventions that target moving students from passive and active engagement toward constructive and interactive engagement.

Providing a context to PSL

A second alternative to procedural learning would be to provide a context for reading PSL. Students require a context for reading PSL and, in the absence of context, students will disengage and even skim or skip sections and information that they perceive as "difficult" (25). Specifically, a distinct shift in students' reading approaches (increased focus and attention, i.e., increased engagement) was found after students were given an evidence-finding task (25). This is in alignment with previous studies showing that structured assignments (e.g., worksheets) promote student engagement (28–29).

Integrating student prior knowledge

In addition to engagement and context, it is generally accepted that prior knowledge is important in learning to read PSL. In fact, students' level of prior knowledge may be more important than their general reading skills for comprehending science texts (30). Even expert PSL readers adopt more superficial reading strategies when encountering PSL outside their area of expertise, suggesting that considerable PSL experience cannot substitute for a lack of prior knowledge (23). However, it is unrealistic to expect undergraduates to have extensive prior knowledge in any scientific field, and so how can we place PSL within the context of prior knowledge that undergraduates do have?

The 5 Core Concepts of Biology as a framework for reading PSL

Biology, as a discipline, has developed the 5 Core Concepts (5CCs) as a conceptual framework describing all potential biology knowledge summarized in five biological scales (molecular, cellular, organismal, population, and ecology) and five overarching concepts that dictate natural biological phenomena or processes (evolution [E]; structure and function [SF]; information flow, exchange, and storage [IFES]; pathways of transformation of energy and matter [PTEM]; and systems [S]) (see Appendix S1 in the supplemental material) (31). The 5CCs represent core concepts that are (i) general enough to be used across biological subdisciplines and (ii) knowledge that every undergraduate biology major ought to know upon graduation. The 5CCs are mirrored in the big ideas outlined by the Next Generation Science Standards (32–33) and the AP Biology Curriculum Framework (34), suggesting that undergraduates may have had some level of exposure to the 5CCs prior to college. Therefore, using the 5CCs as a context of prior knowledge is a promising teaching method for novice undergraduates. Student biology learning and conceptual understanding of specific biological processes can be improved when teaching methods integrate the 5CCs (35–36). For example, introductory biology students were found to draw connections between a CC and a class topic they were taught by simply associating their acquired knowledge to one or more of the 5CCs (35). Therefore, undergraduates may be able to make similar connections between the 5CCs and content contained within PSL.

In this study, we sought to further explore the use of PSL in the undergraduate classroom. First, we investigated whether a 5CCs-based intervention could be used to (i) increase student engagement with PSL, (ii) provide a context for PSL, and (iii) integrate student prior knowledge when reading PSL. Second, we investigated whether a 5CCs-based, semester-long intervention could shift student reading habits to be more expert-like. As no direct assessment for this exists, we instead measured student motivation for reading PSL, their Biology identity, and their perceived learning gains in science.

METHODS

Because our study contains data from 19 students, it is considered a small-*N* study. Insights from small-*N* studies are able to provide an in-depth look into how students learn science (37).

Big Ideas in Biology course

The Big Ideas in Biology (BIIB) is a discussion-based introductory biology course intended to be taken before the introductory biology sequence and where students are introduced to biology through the reading of PSL. In contrast to other introductory biology courses, there are no content-based lectures. Instead, students are introduced to the general principles of biology (as described in *Vision and Change* [31]) and the scientific practices of analyzing data and communicating science through reading PSL. It is the intent of BIIB to give novice students experience with these skills before they begin the content-heavy introductory biology sequence. We teach this course using an interactive classroom activity designed to introduce students to PSL using the 5CCs (11), which are listed in Appendix S1 in the supplemental material.

Students read a total of 14 pieces of PSL over the course of the semester (11). For each piece of PSL, students were given a 5CCs matrix table (see Appendix S2) and were asked to connect the biological content from the piece of PSL to at least 3 corresponding boxes of the table. To assess student PSL analysis through the lens of the 5CCs, the matrix table was included in the first (exam A) and final (exam B) exams of the semester. In exam A students had to read a piece of PSL about the mechanisms of temperature tolerance of coral reefs (38). The article provided information on various physiological and gene expression results regarding the heat tolerance of the tested coral reef populations. In exam B, students had to read and analyze a piece of PSL about limb regeneration in an adult salamander (39). The article provided information on the molecular mechanisms related to nerve and tissue regeneration of the vertebrate's limb.

Student demographics

A total of 27 students enrolled in BIIB in the Fall 2019 semester. Self-identified student data collected by our institution showed that our population overall was 63% women. We had a diverse population of 70% Hispanic or Latino, 19% African American, 7% white, and 4% Asian. We had 48% freshman, 41% sophomores, and 11% seniors. Most of the students had declared a Biology major (74%). Additional majors included Biochemistry (4%) and Environmental Studies (4%). The rest of the students were undeclared.

Qualitative analysis of 5CCs matrix tables

We implemented deductive coding of student 5CCs matrix tables using the conceptual elements (CEs) as our code book (40). CEs are specific statements that articulate key components of the overarching principles mentioned in *Vision and Change*; they are listed in Table 1 and Appendix S3 (Appendix S3 is a more detailed version of Table 1). We linked student responses to the most relevant CE in each given CC. For example, the CE IFES5, "Organisms transmit genes and epigenetic information to their offspring," was used to code student responses in the CC IFES that mentioned passing genes down to offspring. We implemented deductive coding using the CEs because we wanted to compare overall student understanding of the 5CCs among the two different exam papers. Thus, a common, universal codebook was needed.

This deductive approach involved three phases:

- **Phase 1:** Two researchers (K. Chatzikyriakidou and K. Concepcion) read all student responses and took notes on similarities and differences among student responses to the same CC. The goal of this phase was to identify keywords or sentences that exemplified a link between a CE and text from the PSL.
- **Phase 2:** The same two researchers compared their notes in each CC and discussed whether the same CE was reflected in the student responses. When the same CE was reflected in a group of student responses, we considered it a code for all similar student responses for a specific CC. We followed the same coding principles regardless of the amount of correctness in a student's response or the biological scale students used to provide their responses. In cases where a student's response was incomplete or irrelevant to the specific CC, we categorized the response as "other." After discussing all of our codes and with no new codes emerging, we reached consensus and generated a preliminary codebook. We independently coded the first half of student responses of a data set (exam A or B) using the preliminary codebook. We compared our findings and resolved disagreements until a consensus was reached.

TABLE 1
Qualitative analysis of students' use of a 5CCs matrix to understand PSL[a]

Conceptual element	% of students with indicated response	
	Exam A	Exam B
Evolution	$n = 31$	$n = 13$
E2: The phenotypes of living organisms result from the gain and loss of traits along their lineage.	3	16
E4: Phenotypes, based upon underlying genotypes and environmental factors, can be subject to selective pressure.	47	23
E5: Organisms have greater fitness if they have a phenotype that increases their ability to survive and reproduce in a particular environment.	41	46
Other (irrelevant or incomplete statements)	9	15
Structure and function	$n = 14$	$n = 24$
SF1: Biological structures from the molecular to the ecosystem scale and their interactions are determined by chemical and physical properties that both enable and constrain function.	7	62
SF2: Individual structures can be arranged into organized units that enable more complex functions.	7	NI
SF4: Structural features are dynamic and modifications can be made in response to environmental changes that are compensatory to restore lost function or noncompensatory to eliminate functions that are no longer needed.	50	21
Other (irrelevant or incomplete statements)	36	17
Information flow, exchange, and storage	$n = 21$	$n = 14$
IFES1: Information exists in many forms and is relayed within and across biological molecules, cells, tissues, organisms, populations, and ecosystems.	14	71
IFES4: Information from the environment regulates protein synthesis and activity, which control cellular processes and thereby organismal and population-level activity.	33	29
IFES5: Organisms transmit genes and epigenetic information to their offspring.	24	NI
Other (irrelevant or incomplete statements)	29	0
Pathways of transformation of energy and matter	$n = 17$	$n = 11$
PTEM1: Energy is neither created nor destroyed, but can be transformed from one form to another to generate biological activity.	11	9
PTEM2: Input of energy, which can be from different sources, is needed to build and maintain biological entities, thereby lowering entropy in the system.	59	45
PTEM5: Biological entities regulate the synthesis, storage, and mobilization of biological compounds to meet energy demands.	6	9
Other (irrelevant or incomplete statements)	24	36
Systems (S)	$n = 17$	$n = 13$
S1: Biological entities interact through chemical and physical signals that can be transient, depend on spatial organization, and are influenced by environmental factors.	NI	38
S2: Changes in one component of a biological system can affect or be regulated by other components of the same system.	53	8

(Continued on next page)

TABLE 1 (Continued)

Conceptual element	% of students with indicated response	
	Exam A	Exam B
S3. Biological systems can be defined at different scales, interact within and across scales, and together form complex networks.	NI	15
S4: Biological systems include and are affected by biotic and abiotic factors in the environment.	29	NI
S5: Interactions between and among biological entities can generate new system properties.	12	NI
Other (irrelevant or incomplete statements)	6	31

[a]Scales used included molecular, organismal, and population. Conceptual elements (Cary and Branchaw [40]) were used to frame a deductive analysis with the goal of linking student responses to the most relevant CEs in each given CC. Students were requested to fill in at least three cells of the matrix; thus, the *n* values represent the total number of responses received per CC in each exam. Exam A was based on the PSL Palumbi et al., 2014 (38), and Exam B was based on the PSL Kumar et al., 2007 (39). NI, not identified.

This second iteration of analysis resulted in the final codebook.

- **Phase 3:** The same two researchers used the final codebook and independently coded all student responses in each data set. Interrater reliability for each code (the extent to which researchers assigned the same code to the same student response) was measured with a kappa value generated in NVivo. All kappa values were above 0.85, i.e., higher than the 0.65 level suggested in the literature (41). The software package NVivo version 12 (QSR International) was used for all analyses.

Quantitative data collection

We measured the effect of the 5CCs PSL activity on student motivation in reading PSL, student identity as a biologist, and perceived learning gains in science. To do this, we combined selected items originating from three previously validated questionnaires, each explained below:

1. **Motivation in reading PSL.** We implemented "Motivation in Reading Primary Scientific Literature," a previously validated questionnaire that measures student motivation in reading PSL by measuring students purpose for doing the task and their efficacy to achieve (Fig. 1) (42). The questionnaire itself is made up of four subscales:
   a) **Expectancy value theory:** Individuals will put more effort into tasks that they simultaneously perceive to have value and at which they expect to succeed (43–46).
   b) **Self-efficacy:** This scale measures one's self-confidence to perform a behavior (47–50).
   c) **Performance and competence:** This scale measures an individual's confidence levels in relation to their learning environment or disciplinary community, i.e., a college classroom (51, 52).
   d) **Interest:** High interest levels suggest intrinsic motivation (53).

   Motivation items are shown in Appendix S4 and were measured using a Likert scale of 1 (strongly disagree) to 6 (strongly agree). This questionnaire was previously validated using Florida International University (FIU) student data (42). We chose a 6-point scale to increase reliability of responses (54). Motivation scores were used as a proxy for measuring more expert-like thinking: a shift in students' purpose for doing the task and their self-efficacy to achieve could suggest they are approaching reading PSL as more of an expert. This questionnaire was previously validated using FIU student data using a Likert scale of 1 (strongly disagree) to 6 (strongly agree), in order to increase reliability of responses.Motivation items are shown in Appendix S4 and were measured using a Likert scale of 1 (strongly disagree) to 6 (strongly agree). This questionnaire was previously validated using Florida International University (FIU) student data (42). We chose a 6-point scale to increase reliability of responses (54). Motivation scores were used as a proxy for measuring more expert-like thinking: a shift in students' purpose for doing the task and their self-efficacy to achieve could suggest they are approaching reading PSL as more of an expert. This questionnaire was previously validated using FIU student data using a Likert scale of 1 (strongly disagree) to 6 (strongly agree), in order to increase reliability of responses.
2. **Biology identity.** A critical agency framework was adapted that showed that feelings of performance and competence and prior interest in a STEM subject are positive predictors of STEM identities (51, 52). Specifically, performance and competency, measured as one construct, refer to an individual's confidence levels in relation to their disciplinary community, which for this study was the academic Biology community. In addition, interest in a particular subject plays a key role in a person's choice of career, and for this study, interest in academic

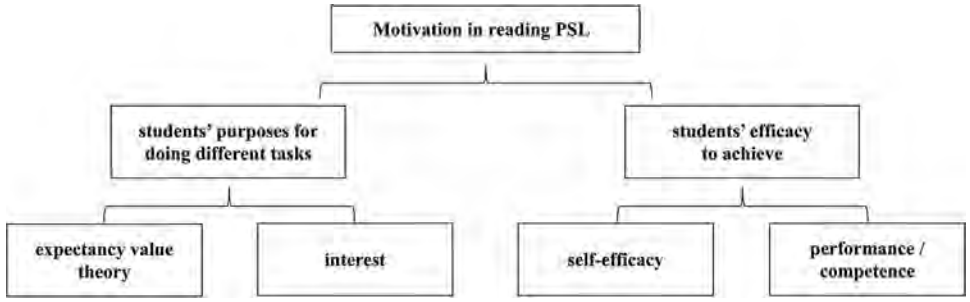


FIG 1. Overview of the motivational constructs used in the development of the "Motivation in reading" PSL questionnaire.

Biology was measured. Six items measuring performance and competence in biology and 3 statements measuring interest in biology were adapted from Godwin et al. (51) by changing the word "physics" to "biology." We have previously validated these items for use with FIU Biology majors (42). The items are shown in Appendix S4 and were measured using a Likert-scale of 1 (strongly disagree) to 6 (strongly agree). We chose a 6-point scale to increase reliability of responses (54).

3. **Student assessment of learning gains.** The Student Assessment of Learning Gains (SALG) instrument (www.salgsite.org) focuses exclusively on the degree to which a course has enabled student learning. The SALG consists of statements about the degree of "gain" (on a 5-point scale) that students perceive they've made in specific aspects of the class. Researchers have established the SALG as a psychometrically sound measure of core learning objectives in undergraduate STEM education (55). Because PSL can serve as a gateway to the research process, we chose to include three items from the subscale "Application of knowledge to research" and three items from the subscale "Attitudes or behaviors as a researcher." The items are shown in Appendix S4 and were measured using a Likert scale of 1 (strongly disagree) to 5 (strongly agree). A 5-point scale was used for SALG, as this assessment was previously validated using this scale.

Distribution of the questionnaire

The questionnaire was administered through Qualtrics (Provo, UT) during the first and last weeks of the semester. A total of 19 complete (paired pre- and postcourse) responses were analyzed. Students received course credit for completing the questionnaire regardless of their decision to allow their data to be used in the study.

Quantitative analysis of questionnaire responses

Average scores of student responses were calculated for each subscale of each questionnaire: (1) motivation in reading PSL, (2) Biology identity, and (3) student attitudes and learning gains. A higher score indicated higher levels of motivation, identity, and learning gains, respectively. Data were analyzed by performing paired *t*-tests with the data collected in the beginning and end of the semester (pre-post analysis) and examined whether the differences in average student scores per scale of each questionnaire were significantly different ($P < 0.05$). All analyses were performed in R (56).

Ethics statement

All data were collected in accordance with an approved FIU Institutional Review Board protocol (IRB-17-0276).

RESULTS

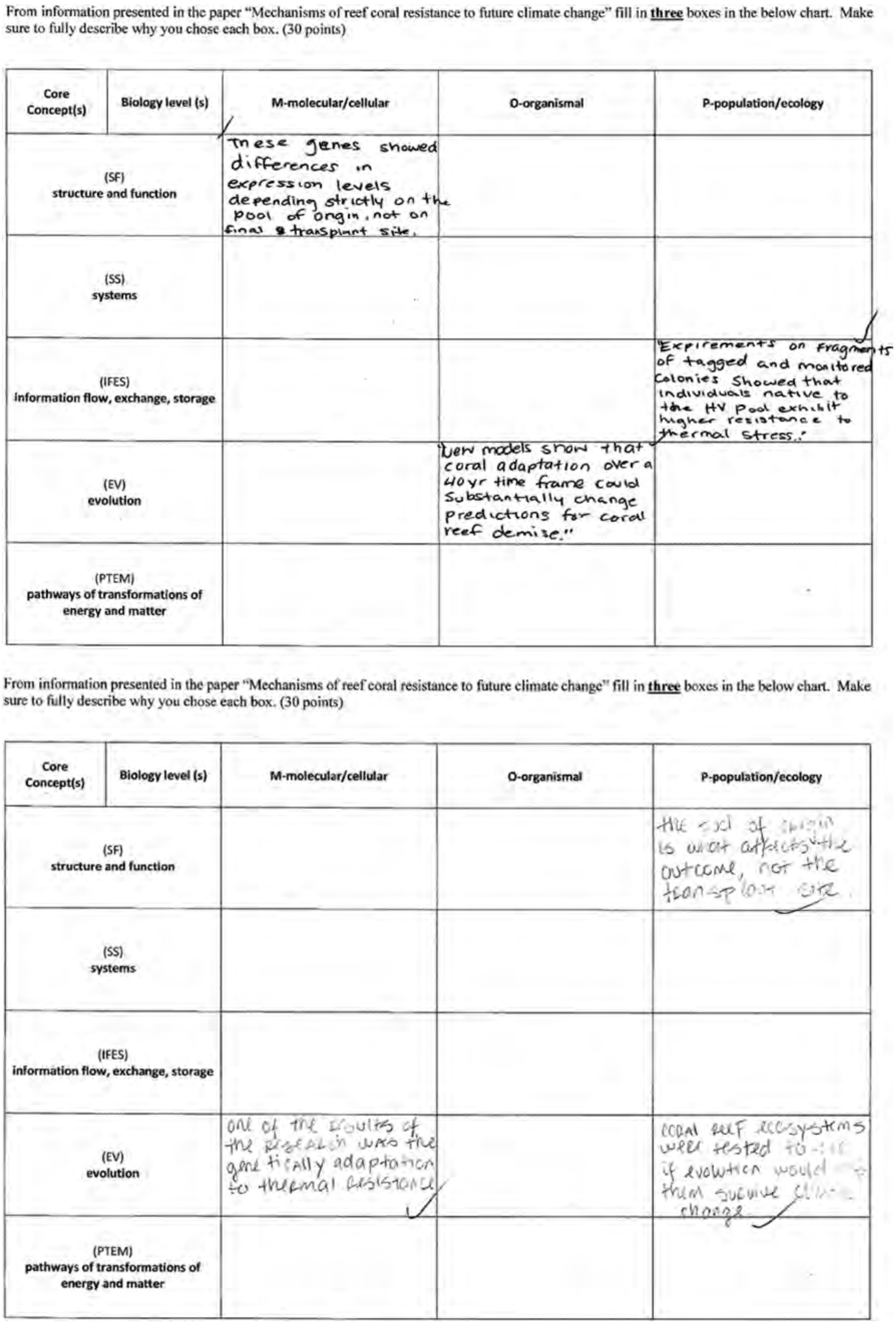
To determine whether a 5CCs-based intervention could be used to (i) increase student engagement with PSL, (ii) provide a context for PSL, and (iii) integrate student prior knowledge when reading PSL, we evaluated 5CCs matrix tables (a structured, active-learning task) designed to help undergraduates place the content found within PSL into the larger context of the 5CCs (a knowledge framework for undergraduates).

Increased student engagement with PSL

According to the ICAP hypothesis (26–27), students who generate notes and/or summaries in their own words are considered constructive (mode 3). The 5CCs matrix table pushes students to this mode, and we saw evidence of this in the matrix tables themselves (Fig. 2). Students were able to connect content from the PSL to one of the 5CCs and one of the biological scales by writing a summary in their own words. For instructors wanting to adapt a version of the 5CCs activity with their own students, we provide information on how we graded the matrix table as an exam in a previous report (Chatzikyriakidou et al., 2021 [11]).

Providing a context for PSL

We deductively coded student PSL 5CCs matrix tables. To start, we did a general analysis of which 5CCs students



From information presented in the paper "Mechanisms of reef coral resistance to future climate change" fill in **three** boxes in the below chart. Make sure to fully describe why you chose each box. (30 points)

Core Concept(s) / Biology level (s)	M-molecular/cellular	O-organismal	P-population/ecology
(SF) structure and function	These genes showed differences in expression levels depending strictly on the pool of origin, not on final transplant site.		
(SS) systems			
(IFES) information flow, exchange, storage			"Expirements on Fragments of tagged and monitored Colonies Showed that individuals native to the HV Pool exhibit higher resistance to thermal stress."
(EV) evolution		"New models show that coral adaptation over a 40yr time frame could Substantially change predictions for coral reef demise."	
(PTEM) pathways of transformations of energy and matter			

From information presented in the paper "Mechanisms of reef coral resistance to future climate change" fill in **three** boxes in the below chart. Make sure to fully describe why you chose each box. (30 points)

Core Concept(s) / Biology level (s)	M-molecular/cellular	O-organismal	P-population/ecology
(SF) structure and function			the [illegible] of origin is what affects the outcome, not the transplant site.
(SS) systems			
(IFES) information flow, exchange, storage			
(EV) evolution	one of the results of the research was the genetically adaptation to thermal resistance		coral reef ecosystems were tested to [illegible] if evolution would [illegible] them survive [illegible] change
(PTEM) pathways of transformations of energy and matter			

FIG 2. Example of the student 5CCs matrix tables, showing students writing summaries of PSL content in their own words.

connected to the most for each piece of PSL. For exam A, which was based on Palumbi et al., 2014 (38), students most often connected to the concepts of E and IFES, followed by S and PTEM, based on the total responses shown in Appendix S3. Although all three biological scales were seen in student responses, population was the most common in E and S, while molecular was the most popular in SF, PTEM, and IFES. For exam B, students connected Kumar et al., 2007 (39) most often to the concepts of SF and IFES, followed by E, PTEM, and S. These findings are in accordance with the content of the papers assigned to students during exams A and B. Collectively, we consistently saw students were able to place content from PSL into the matrix chart, using a variety of 5CCs and biological scales, suggesting that the 5CCs matrix table provides a context for students as they read PSL.

Integrating student prior knowledge when reading PSL

We performed a more detailed deductive coding of student responses using the CEs as a framework. For each of the 5CCs, there were at least 3 CEs identified by students, although individual CEs varied for exam A or B (Table 1; see also Appendix S3 in the supplemental material) except for the CC Evolution (E).

In Evolution, the CEs were related to the relationships between selection or adaptation and phenotype of a population of corals in exam A, and of proteins, individuals, or populations of salamanders in exam B. Regarding the CC SF, the common CEs were those referring to the interrelation of structure and function as well as the changes of biological structures due to environmental factors. The CE that was seen only in exam A referred to the structure and function of complex structures made of simpler ones.

Regarding the CCs IFES and PTEM, a majority of students responded with examples of molecular scale biology; however, the population scale was also common in exam A, which referred to a population of corals. The common IFES CEs in both exams were related to types of communication among biological structures and the effects of environmental factors on gene expression. The CE that was seen only in exam A referred to epigenetics. The common PTEM CEs in both exams referred to transformation of energy, input of energy, and the relationship between use of energy and use of matter. It is worth noting that the CE PTEM2 refers to entropy; however, in this class students do not learn about entropy and we applied this code mostly for its first part, "Input of energy, which can be from different sources, is needed to build and maintain biological entities."

In the CC for Systems (S), in exam A students wrote about changes in system components and the environmental effects on system properties, as well as the effects of biological interactions on system properties of a coral reef ecosystem or population in general. In exam B, students wrote about changes in system components, the use of signals for biological interactions, and the complexity of systems, focusing mainly on the molecular and organismal scales. Because experts rely on prior knowledge to read PSL, we reasoned that if students were able to connect to more than one CE, which were more specific than the 5CCs, then this indicated that they were learning to draw from prior knowledge and were not simply rewriting the headings on the 5CCs matrix table.

To determine whether a 5CCs-based, semester-long intervention could shift student reading habits to more expert-like, we measured students' (1) motivation for reading PSL, (2) Biology identity, and (3) attitudes toward research.

Student motivation for reading PSL

We found significant pre- versus postcourse differences in students' expectancy values, self-efficacy, and performance and competence in reading PSL (Fig. 3). Student interest in PSL increased, but not significantly.

Students' Biology identity

We saw significant increases in students' Biology identity, i.e., their performance and competence and interest in Biology (Fig. 4). Although precourse scores were high, with 4.78 and 5.25 for performance or competence and interest, respectively, our course structure of reading PSL in class seemed to promote student effect for Biology.

Student attitudes toward research

Students self-reported learning significantly more about research in their discipline in both categories of student learning gains measured in this study (Fig. 5). Students reported significantly higher gains in applying this course's knowledge to research as well as feeling more like a researcher.

DISCUSSION

In this study, we investigated whether a 5CCs-based intervention could be used to (i) increase student engagement with PSL, (ii) provide a context for PSL, and (iii) integrate student prior knowledge when reading PSL. We also investigated whether a 5CCs-based, semester-long intervention could shift student PSL reading habits to more expert-like by measuring students' motivation for reading PSL, their Biology identity, and their perceived learning gains related to research.

Using the 5CCs as a framework for learning to read PSL

We hypothesized that the 5CCs of Biology would serve both as a context for students as well as a source of prior knowledge. Our data (Fig. 2; see also Appendix S3 in the supplemental material) support our hypothesis.

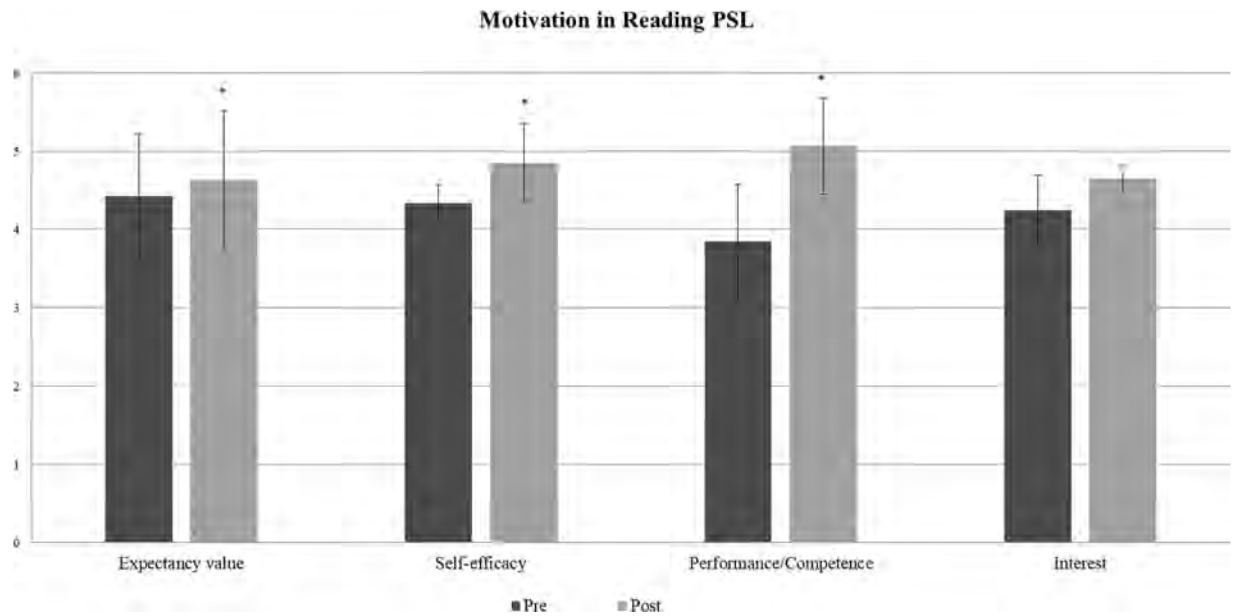


FIG 3. Pre- and postcourse comparisons (paired *t* test, $n = 19$) of student scores for the "Motivation in reading" PSL. Items used are shown in Appendix S4. A 6-point Likert scale was used. Error bars show the SD and asterisks indicate significant differences ($P < 0.05$) between pre- and postcourse scores.

What was found to be most valuable about the 5CCs matrix chart was students generating notes and/or summaries of the content contained within PSL in their own words. Creating summaries of PSL is valuable for two reasons. First, the ICAP framework considers students who generate notes and/or summaries in their own words (mode 3) to be constructive (24, 26, 27). This is important, as expert PSL readers were found to engage with PSL at a constructive level (mode 3) more often than students (24). Therefore, engaging with the 5CCs matrix table while reading PSL helped to push the students toward more expert-like reading behaviors.

Second, expert PSL readers reduce cognitive load while reading PSL through summarizing and note-taking at a rate three times that of novice students (24). Therefore, it was suggested that instructors implement interventions designed to prompt novice readers to summarize information constructively as they read PSL (24). Summarizing allows readers to connect different pieces of the text to form a cohesive

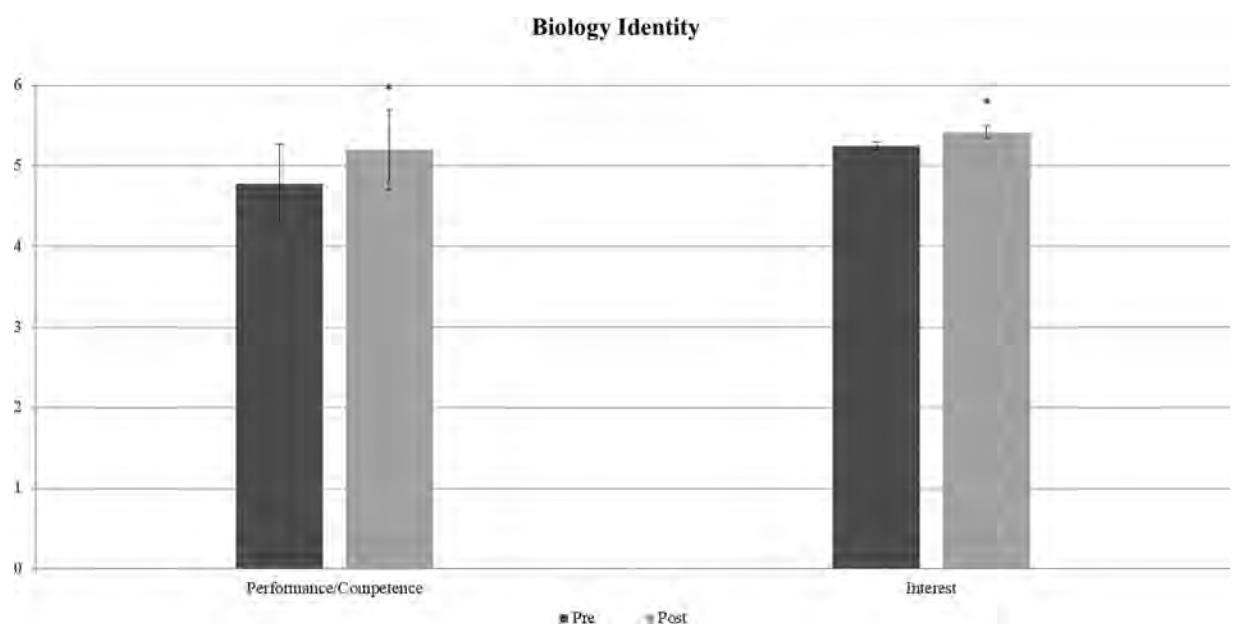


FIG 4. Pre- and postcourse comparisons (paired *t* test, $n = 19$) of student scores for biology identity. Items used are shown in Appendix S4. A 6-point Likert scale was used. Error bars show the SD and asterisks indicate significant differences ($P < 0.05$) between pre- and postcourse scores.

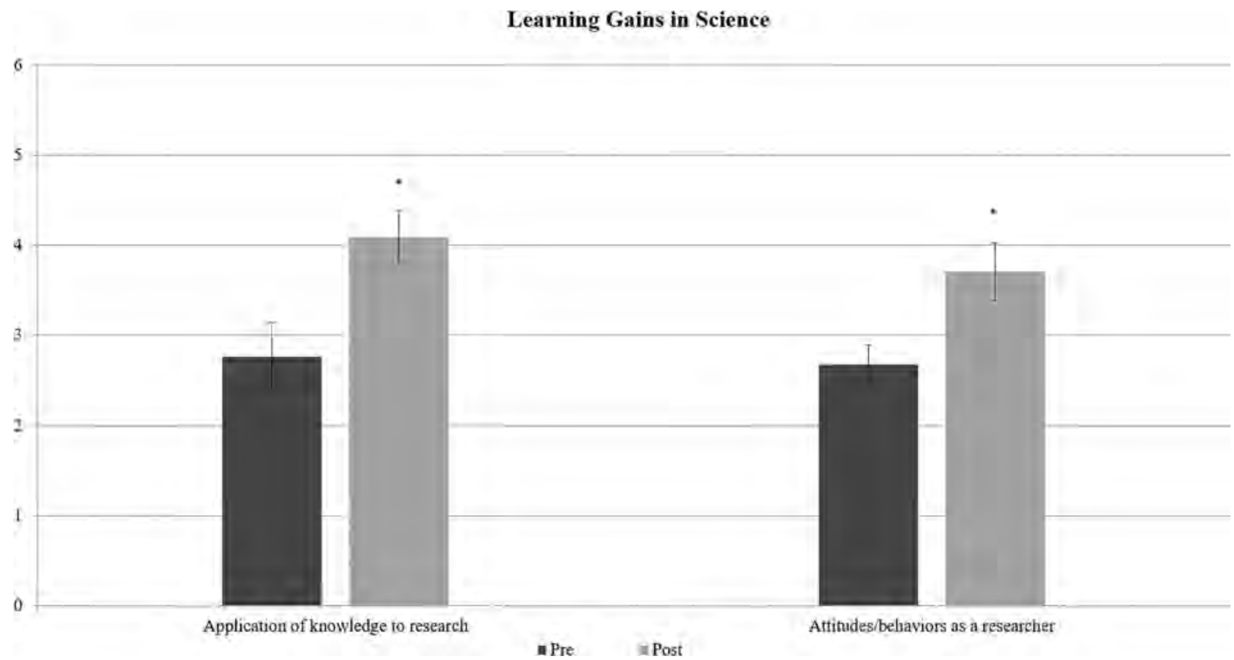


FIG 5. Pre- and postcourse comparisons (paired *t* test, $n = 19$) of student scores for student attitudes and learning gains. Items used are shown in Appendix S4. A 5-point Likert scale was used. Error bars show the SD and asterisks indicate significant differences ($P < 0.05$) between pre- and postcourse scores.

idea, rather than evaluating separate pieces of information in isolation (57). Similarly, the 5CCs were developed as a way to connect different aspects of biology as a cohesive idea rather than as separate biological facts. In our study, qualitative analysis showed that the PSL 5CCs matrix table had the potential to help students reduce their cognitive load by guiding their conceptual understanding of the PSL content and connecting it to their prior knowledge. Thus, asking students to summarize the content of the PSL they connect to specific CCs provides students two parallel avenues (increased engagement and reduced cogitative load) to engage with PSL.

Does using the 5CCs as a framework for reading PSL shift student PSL reading habits to more expert-like?

We measured student motivations for reading PSL, because motivation determines why individuals choose to do different activities (20). For novice students learning to read PSL, improving their underlying motivations related to PSL may be as important as teaching them the mechanics of reading PSL. We want our students to value PSL and to choose to engage with it, in their academic career and beyond, in the way that practicing scientists do.

The Motivation in Reading PSL questionnaire measured students' purposes for engaging with PSL using the constructs of (i) expectancy value theory and (ii) interest in reading PSL (Fig. 1). We found significant pre- versus postcourse differences in students' expectancy values, suggesting that students perceived reading PSL to have value and that it is a task in which they expect to succeed (43–46). An increase in expectancy value also suggests that students' purposes for engaging with PSL increased over the course of the semester, implying a shift toward expert-like behavior. We did not see an increase in interest in reading PSL, which is noteworthy, as promoting student interest in reading PSL remains a challenge for educators.

We also saw a significant increase in students' self-efficacy and performance and competence in reading PSL, which confirmed an increase in students' efficacy to achieve while reading PSL. These data suggest that students are starting to believe that they can perform well and are more likely to view the difficult task of reading PSL as something to be mastered rather than something to be avoided (47–50).

We also investigated whether the 5CCs intervention helped students see themselves as biologists. If students' Biology identities increase, as they did in our study, then they are more likely to see themselves as biologists. We saw significant increases in performance and competence and interest in biology. Performance and competence refer to an individual's confidence levels in relation to their disciplinary community, which, for this study, would be the academic Biology community. Seeing an increase here is significant, as this indicates that the 5CCs intervention helped students see themselves as someone who can perform within the Biology community itself.

Interest in a particular subject plays a key role in a person's choice of career, and for this study student interest in biology increased. One possibility for this shift is that almost half of our student population was incoming freshmen and their interest in biology was likely still developing during this class. A second way to interpret this shift is that learning how to read PSL through the 5CCs framework really helped connect students to biological content, and this positive engagement helped to increase their interest in biology.

Because PSL can serve as a gateway to the research process, we wanted to know whether increasing student engagement with PSL could also promote research skills. We saw a shift in student assessment of their learning gains in the categories of "application of knowledge to research" and "attitudes or behaviors as a researcher." This is important for three reasons. First, the specific SALG questions we chose to include in our data analysis were skills-focused, suggesting that our students are shifting toward viewing reading PSL as a skill. Second, items in the "attitudes or behaviors as a researcher" construct overlapped with our identity items, providing additional support that the shift we saw in Biology identity is authentic. Third, students perceiving that they had gained research skills as the result of reading PSL has reverberating implications, as PSL is available at significantly less cost and higher scalability than traditional lab-based courses. Thus, colleges and universities with limited resources can consider using PSL-based learning as a way to bring authentic science practices to their students.

Limitations of our study

While our study involved a small group of students, the demographic composition of our participants is representative of the overall Biology department population at our institution. Although student prior knowledge was not directly measured, it was assumed to be lower than any other course, since the BIIB class is taken before the introductory biology sequence. It will be interesting to repeat our study in other types of institutions, with more advanced biology students, and with a larger student population to confirm our results.

Future directions

We acknowledge that this study took place in a Biology classroom with data collected from Biology students. This was due to the research team being members of Biology departments with direct access to students in Biology courses. However, we believe our intervention can be adapted for use in other disciplines. While the 5CCs framework is specific to biology, it is highly likely that chemistry or physics PSL could be analyzed by undergraduates using similar discipline-specific conceptual frameworks. The Motivation in Reading PSL is universal and could be used to gauge the effect on student motivation for reading PSL, similar to this study.

While collecting data mostly from introductory students in this study was not a limitation, it is possible that more advanced students would respond differently to the 5CCs matrix table, due to their different prior knowledge in biology. It would also be of interest to determine the number of times a student would have to complete the 5CCs PSL table to see similar results. Our students completed the 5CCs PSL table 14 times over the course of a semester. Can similar gains be seen with students only using the table 5 times? Or even 3 times? These data would be valuable in efforts to scale the 5CCs PSL intervention for use in larger courses.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 1.2 MB.

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REFERENCES

1. Sato BK, Kadandale P, He W, Murata PMN, Latif Y, Warschauer M. 2014. Practice makes pretty good: assessment of primary literature reading abilities across multiple large-enrollment biology laboratory courses. CBE Life Sci Educ 13:677–686. https://doi.org/10.1187/cbe.14-02-0025.
2. Hoskins SG, Stevens LM, Nehm RH. 2007. Selective use of the primary literature transforms the classroom into a virtual laboratory. Genetics 176:1381–1389. https://doi.org/10.1534/genetics.107.071183.
3. Round JE, Campbell AM. 2013. Figure facts: encouraging undergraduates to take a data-centered approach to reading primary literature. CBE Life Sci Educ 12:39–46. https://doi.org/10.1187/cbe.11-07-0057.
4. Wenk L, Tronsky L. 2011. First-year students benefit from reading primary research articles. J College Sci Teach 40:60–67.
5. Krontiris-Litowitz J. 2013. Using primary literature to teach science literacy to introductory biology students. J Microbiol Biol Educ 14:66–77. https://doi.org/10.1128/jmbe.v14i1.538.
6. Sandefur CI, Gordy C. 2016. Undergraduate journal club as an intervention to improve student development in applying the scientific process. J College Sci Teach 45:52–58.
7. McCartney M, Childers C, Baiduc RR, Barnicle K. 2018. Annotated primary literature: a professional development opportunity in science communication for graduate students and postdocs. J Microb Biol Educ 19:19.1.24. https://doi.org/10.1128/jmbe.v19i1.1439.
8. Kararo M, McCartney M. 2019. Annotated primary scientific literature: a pedagogical tool for undergraduate courses. PLoS Biol 17:e3000103. https://doi.org/10.1371/journal.pbio.3000103.
9. Schmid KM, Wiles JR. 2019. An introduction to biological research course for undergraduate biology students. J Coll Sci Teach 049:48–52. https://doi.org/10.2505/4/jcst19_049_01_48.

10. Schmid KM, Dunk RDP, Wiles JR. 2021. Early exposure to primary literature and interactions with scientists influences novice students' views on the nature of science. J College Sci Teach 50:40–47.
11. Chatzikyriakidou K, Manrique C, Janelle Tacloban M, McCartney M. 2021. Exploring primary scientific literature through the lens of the 5 Core Concepts of Biology. CourseSource 8. https://doi.org/10.24918/cs.2021.5.
12. Choe SWT, Drennan PM. 2001. Analyzing scientific literature using a jigsaw group activity: piecing together student discussions on environmental research. J College Sci Teach 30:328–330.
13. Segura-Totten M, Dalman NE. 2013. The CREATE method does not result in greater gains in critical thinking than a more traditional method of analyzing the primary literature. J Microbiol Biol Educ 14:166–175. https://doi.org/10.1128/jmbe.v14i2.506.
14. Gottesman AJ, Hoskins SG. 2013. C.R.E.A.T.E. cornerstone: introduction to scientific thinking, a new course for STEM-interested freshmen, demystifies scientific thinking through analysis of scientific literature. CBE Life Sci Educ 12:59–72. https://doi.org/10.1187/cbe.12-11-0201.
15. Hoskins SG, Lopatto D, Stevens LM. 2011. The C.R.E.A.T.E. approach to primary literature shifts undergraduates' self-assessed ability to read and analyze journal articles, attitudes about science, and epistemological beliefs. CBE Life Sci Educ 10:368–378. https://doi.org/10.1187/cbe.11-03-0027.
16. Kenyon KL, Onorato ME, Gottesman AJ, Hoque J, Hoskins SG. 2016. Testing C.R.E.A.T.E. at community colleges: an examination of faculty perspectives and diverse student gains. CBE Life Sci Educ 15:ar8. https://doi.org/10.1187/cbe.15-07-0146.
17. Murray TA. 2014. Teaching students to read the primary literature using POGIL activities: POGIL using the primary literature. Biochem Mol Biol Educ 42:165–173. https://doi.org/10.1002/bmb.20765.
18. Stevens LM, Hoskins SG. 2014. The C.R.E.A.T.E. strategy for intensive analysis of primary literature can be used effectively by newly trained faculty to produce multiple gains in diverse students. CBE Life Sci Educ 13:224–242. https://doi.org/10.1187/cbe.13-12-0239.
19. Plavén-Sigray P, Matheson GJ, Schiffler BC, Thompson WH. 2017 The readability of scientific texts is decreasing over time. Elife 6:e27725. https://doi.org/10.7554/eLife.27725.001.
20. National Research Council. 2000. How people learn: brain, mind, experience, and school. National Academy Press, Washington, DC.
21. Tenopir C, King DW. 2003. Communication patterns of engineers, p 149–161. John Wiley & Sons, Hoboken, NJ.
22. Tenopir C, King DW, Edwards S, Wu L. 2009. Electronic journals and changes in scholarly article seeking and reading patterns. Aslib Proc 61:5–32. https://doi.org/10.1108/00012530910932267.
23. Hubbard KE, Dunbar SD. 2017. Perceptions of scientific research literature and strategies for reading papers depend on academic career stage. PLoS One 12:e0189753. https://doi.org/10.1371/journal.pone.0189753.
24. Nelms AA, Segura-Totten M. 2019. Expert–novice comparison reveals pedagogical implications for students' analysis of primary literature. CBE Life Sci Educ 18:ar56. https://doi.org/10.1187/cbe.18-05-0077.
25. Lennox R, Hepburn K, Leaman E, van Houten N. 2020. 'I'm probably just gonna skim': an assessment of undergraduate students' primary scientific literature reading approaches. Int J Sci Educ 42:1409–1429. https://doi.org/10.1080/09500693.2020.1765044.
26. Chi MTH. 2009. Active-constructive-interactive: a conceptual framework for differentiating learning activities. Top Cogn Sci 1:73–105. https://doi.org/10.1111/j.1756-8765.2008.01005.x.
27. Chi MTH, Wylie R. 2014. The ICAP framework: linking cognitive engagement to active learning outcomes. Educ Psychol 49:219–243. https://doi.org/10.1080/00461520.2014.965823.
28. Weir LK, Barker MK, McDonnell LM, Schimpf NG, Rodela TM, Schulte PM. 2019. Small changes, big gains: a curriculum-wide study of teaching practices and student learning in undergraduate biology. PLoS One 14:e0220900. https://doi.org/10.1371/journal.pone.0220900.
29. Koretsky M, Keeler J, Ivanovitch J, Cao Y. 2018. The role of pedagogical tools in active learning: a case for sense-making. Int J STEM Educ 5:18. https://doi.org/10.1186/s40594-018-0116-5.
30. Ozuru Y, Dempsey K, McNamara DS. 2009. Prior knowledge, reading skill, and text cohesion in the comprehension of science texts. Learn Instruct 19:228–242. https://doi.org/10.1016/j.learninstruc.2008.04.003.
31. American Association for the Advancement of Science. 2010. Vision and change in undergraduate education: a call to action. AAAS, Washington, DC. https://visionandchange.org/wp-content/uploads/2011/03/Revised-Vision-and-Change-Final-Report.pdf.
32. National Research Council. 2013. Next generation science standards: for states, by states. National Academies Press, Washington, DC.
33. National Research Council. 2015. Guide to implementing the next generation science standards. National Academies Press, Washington, DC.
34. Wood WB. 2009. Revising the AP Biology curriculum. Science 325:1627–1628. https://doi.org/10.1126/science.1180821.
35. Chatzikyriakidou K, Tacloban M-J, Concepcion K, Geiger J, McCartney M. 2021. Student association of lecture content with the Five Core Concepts of Biology: novel results from an introductory biology course. J Microbiol Biol Educ 22:e00105-21. https://doi.org/10.1128/jmbe.00105-21.
36. Couch BA, Wright CD, Freeman S, Knight JK, Semsar K, Smith MK, Summers MM, Zheng Y, Crowe AJ, Brownell SE. 2019. GenBio-MAPS: a programmatic assessment to measure student understanding of Vision and Change core concepts across general biology programs. CBE Life Sci Educ 18:ar1. https://doi.org/10.1187/cbe.18-07-0117.
37. Gouvea J. 2017. Insights from small-N studies. CBE Life Sci Educ 16:e4. https://doi.org/10.1187/cbe.17-06-0110.
38. Palumbi SR, Barshis DJ, Traylor-Knowles N, Bay RA. 2014. Mechanisms of reef coral resistance to future climate change. Science 344:895–898. https://doi.org/10.1126/science.1251336.
39. Kumar A, Godwin JW, Gates PB, Garza-Garcia AA, Brockes JP. 2007. Molecular basis for the nerve dependence of limb regeneration in an adult vertebrate. Science 318:772–777. https://doi.org/10.1126/science.1147710.

40. Cary T, Branchaw J. 2017. Conceptual elements: a detailed framework to support and assess student learning of biology core concepts. CBE Life Sci Educ 16:ar24. https://doi.org/10.1187/cbe.16-10-0300.
41. Syed M, Nelson SC. 2015. Guidelines for establishing reliability when coding narrative data. Emerg Adult 3:375–387. https://doi.org/10.1177/2167696815587648.
42. Chatzikyriakidou K, McCartney M. 2022. Motivation in reading primary scientific literature: a questionnaire to assess student purpose and efficacy in reading disciplinary literature. Int J Sci Educ 44:1230–1250. https://doi.org/10.1080/09500693.2022.2073482.
43. Eccles J, Adler T, Futterman R, Goff S, Kaczala C, Meece J. 1983. Achievement and achievement motives: psychological and sociological approaches, p 75–146. *In* Spence JT (ed), Achievement and achievement motivation. WH Freeman, San Francisco, CA.
44. Eccles JS, Wigfield A. 1995. In the mind of the actor: the structure of adolescents' achievement task values and expectancy-related beliefs. Pers Soc Psychol Bull 21:215–225. https://doi.org/10.1177/0146167295213003.
45. Eccles JS, Wigfield A. 2002. Motivational beliefs, values, and goals. Annu Rev Psychol 53:109–132. https://doi.org/10.1146/annurev.psych.53.100901.135153.
46. Wigfield A, Eccles JS. 2000. Expectancy: value theory of achievement motivation. Contemp Educ Psychol 25:68–81. https://doi.org/10.1006/ceps.1999.1015.
47. Bandura A. 1986. Social foundations of thought and action: a social cognitive theory. Prentice Hall, Englewood Cliffs, NJ.
48. Bandura A. 1989. Human agency in social cognitive theory. Am Psychol 44:1175–1184. https://doi.org/10.1037/0003-066x.44.9.1175.
49. Bandura A. 1993. Perceived self-efficacy in cognitive development and functioning. Educ Psychol 28:117–148. https://doi.org/10.1207/s15326985ep2802_3.
50. Bandura A. 1997. Self-efficacy: the exercise of control. WH Freeman, New York.
51. Godwin A, Potvin G, Hazari Z, Lock R. 2016. Identity, critical agency, and engineering: an affective model for predicting engineering as a career choice. J Eng Educ 105:312–340. https://doi.org/10.1002/jee.20118.
52. Carlone HB, Johnson A. 2007. Understanding the science experiences of successful women of color: science identity as an analytic lens. J Res Sci Teach 44:1187–1218. https://doi.org/10.1002/tea.20237.
53. Fishbach A, Woolley K. 2022. The structure of intrinsic motivation. Annu Rev Organ Psychol Organ Behav 9:339–363. https://doi.org/10.1146/annurev-orgpsych-012420-091122.
54. Chomeya R. 2010. Quality of psychology test between Likert scale 5 and 6 points. J Social Sci 6:399–403. https://doi.org/10.3844/jssp.2010.399.403.
55. Seymour E, Wiese D, Hunter A, Daffinrud SM. 2000. Creating a better mousetrap: on-line student assessment of their learning gains. Originally presented at the National Meetings of the American Chemical Society Symposium, "Using real-world questions to promote active learning." http://www.salgsite.org/docs/SALGPaperPresentationAtACS.pdf.
56. R Core Team. 2022. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
57. Dunlosky J, Rawson KA, Marsh EJ, Nathan MJ, Willingham DT. 2013. Improving students' learning with effective learning techniques: promising directions from cognitive and educational psychology. Psychol Sci Public Interest 14:4–58. https://doi.org/10.1177/1529100612453266.