

Student Association of Lecture Content with the Five Core Concepts of Biology: Novel Results from an Introductory Biology Course

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Challenges in integration of concepts persist among undergraduate biology students. The 5 core concepts (5CCs) of biology presented in *Vision and Change* provide a comprehensive, concept-based description of the knowledge of biology, summarized in five main biological scales and five overarching principles that dictate natural biological phenomena and processes. The goal of this study was to collect information on students' interpretations of three introductory biology topics, (i) aquaporins, (ii) aerobic respiration, and (iii) DNA transcription, while associating their knowledge of these topics with the 5CCs. During three separate exam review sessions, students of a conventional lecture-based introductory biology class were asked to provide short responses of how each of the 5CCs related to the given class topic. An inductive coding analysis of student responses was performed to reveal the main connections students made between each of the three topics and the 5CCs. We found that for some core concepts it was easier for students to draw connections to a simple topic, such as aquaporins, while for other core concepts it was easier to draw connections to a multistep phenomenon, such as aerobic respiration. Although student connections were simple associations between a CC and a class topic, exploratory studies such as this one can be an important step toward designing teaching practices that are aligned with *Vision and Change* recommendations and could advance student conceptual understanding and integration of biological knowledge.

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

INTRODUCTION

The need for instructional approaches that help students make connections both between subdisciplines of biology, as well as across disciplines, has been nationally recognized (1, 2). At the same time, we know that current undergraduates struggle with conceptual learning and understanding of biology (3–9). In an effort to address the needs for biology education reform, the National Science Foundation (NSF) and the American Association for the Advancement in Science (AAAS) in 2011 published the *Vision and Change* report, which introduced the five overarching core concepts in biology (5CCs).

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Vision and Change (2) provides a comprehensive, concept-based description of the knowledge of biology, summarized in five main biological scales and five core concepts (5CCs, Fig. 1) that altogether dictate natural biological phenomena or processes. Since the first publication of *Vision and Change*, effort has been put into developing conceptual frameworks that could be easily adapted to various course syllabi (10, 11). Using these frameworks, the Biology Core Concept Instrument (BCCI) tool was specifically designed to measure first-year students' ability to identify and describe concepts represented in biological phenomena (12). More recently, we have developed a 5CCs lesson plan with the aim to advance student science process skills, such as analyzing primary scientific literature (PSL) while using the 5CCs (13). While biology education researchers continue to develop 5CCs-related activities and surveys that can be used to measure student understanding of the 5CCs (14), there is very little literature discussing what students learn when they are taught with the 5CCs or how they might be actually using the 5CCs to learn biology in class.

With this study, we aimed to investigate undergraduate student perceptions of previously taught class content while using the 5CCs. Thus, the goal of this study was to collect information on students' explanations of three introductory

EVOLUTION <i>What do we know about the evolution of this biological unit or process?</i>	
STRUCTURE AND FUNCTION <i>Do we know what structure is required for a particular function?</i>	
INFORMATION FLOW, EXCHANGE AND STORAGE <i>What type of "communication" is needed to drive this biological process?</i>	
PATHWAYS OF TRANSFORMATION OF ENERGY AND MATTER <i>Is anything getting transformed (used or produced)?</i>	
SYSTEMS <i>What parts or phases make up this biological unit or process?</i>	

FIG 1. A blank copy of worksheet used in this study. During each of the three review sessions, each student was given a copy of this worksheet and asked to associate one of the three topics, aquaporins, aerobic respiration, or DNA transcription, with the 5CCs.

biology topics, aquaporins, aerobic respiration, and DNA transcription, while associating their knowledge of each topic with the 5CCs. We were primarily interested in investigating student interpretation of each CC individually within the context of a given class topic. We did not ask students to connect the various CCs with each other or with the various biological scales, but we compare and contrast our findings on students' 5CCs interpretation of simple (e.g., aquaporins) as opposed to multistep phenomena (e.g., aerobic respiration and DNA transcription).

We are aware of the need to provide students with teaching approaches that promote expert-like conceptual understanding of biology or help educators examine student understanding of introductory biology class content. Although student conceptual understanding was not directly measured, exploratory studies such as this one can be an important step toward designing teaching practices aligned with *Vision and Change* recommendations and could potentially advance student conceptual understanding of introductory biology course content.

METHODS

General Biology I course

Students in this study ($n = 173$; 65% first-year students, 53% biology majors) were enrolled in a conventional lecture-based section of a General Biology I course during Fall 2019.

This is the first semester of introductory biology course, offered at a Carnegie R1-ranked land grant institution, and is a requirement for all biology majors. The students met with the instructor for 75 min twice a week. Course content of General Biology I focuses on fundamental cellular and molecular processes, including genetics, and students are assessed through four mandatory exams plus an optional final exam. An exam review session is linked to each course exam and is considered part of the regular class schedule. The main reading source of this course is Campbell's 10th Ed. (15). The course outcomes for General Biology I have been aligned with *Vision and Change* (2) and the participating instructor had previous knowledge of the 5CCs; however, no explicit in-class activities incorporating the 5CCs had previously been in place.

Student prior knowledge of 5CCs

Due to the novelty of the in-class activity used in this study, and lack of other reporting data on student 5CCs understanding, we measured students' prior 5CCs knowledge. We primarily wanted to know whether increased student familiarity with a CC would correlate with better responses in that CC. Prior to the 5CCs in-class activity, we asked students to report their familiarity with any of the 5CCs (prompt "Which of these concepts are you familiar with?") via an online questionnaire (16), along with consent to participate in the study. There was no description provided about the 5CCs given to students, as we did not want to influence their self-reported scores. The questionnaire was distributed using Canvas classroom management software as a voluntary, precourse assignment, and students who completed it were given extra credit points regardless of whether they consented to participate in the study. The research project was approved by FIU IRB (IRB-19-0253).

5CCs in-class activity

The instructor introduced students to the 5CCs at the beginning of the semester using the 5CCs example statements provided in the BioCore Guide (10). The instructor chose to present statements that were more relevant to the material covered in class.

To measure student interpretation of previously taught biology content while using the 5CCs, students were asked to participate in a short in-class activity each time they had an exam review session, totaling up to three 5CCs in-class activities during the semester. The 5CCs in-class activities took place during the last 15 min of each exam review session and student participation was voluntary. The three topics used in the 5CCs in-class activities were in this order: aquaporins, aerobic respiration, and DNA transcription. We chose these topics based on the chronological order of the material taught in class and the importance of knowing this content before an upcoming exam.

In each review session, students were provided with a single page worksheet previously designed for similar 5CCs

activities (13) (Fig. 1). The worksheet includes a matrix table with five rows, each containing a core concept and three columns, containing the biological scales of molecular/cellular, organismal, and population/ecology, respectively. We modified the worksheet to include clarification questions for each CC, to ensure that students would think of a response relevant to the class topic and the specific CC. The clarification questions were written in a general manner, applicable to all three class topics, in order to use the same worksheet in all three in-class activities. For each CC question, students were asked to provide a short answer based on their personal knowledge and understanding of the specific class topic. In addition, we instructed students to fill in only the molecular/cellular column, since all three topics used in this study were molecular/cellular biological processes. Discussion among students was allowed since this was not an individually graded assessment and we wanted to help students explain or share their thoughts with others.

Out of the total 173 students, 84 consented to participate in this study and a collection of 69 to 77 student responses were returned during each in-class activity. The deviation between consented and actual populations was due to different numbers of students being present in class during each exam review session. We qualitatively analyzed all the worksheets we gathered per class topic as three independent data sets.

Qualitative analysis

Student worksheet responses were analyzed using thematic analysis (17) and the software package NVivo version 12 (18). The goal of this analysis was to identify themes in student responses for each of the 5CCs and class topic (aquaporins, aerobic respiration, and DNA transcription). The same inductive approach was completed for each class topic and involved the three phases, described below.

Phase 1. In phase 1, two researchers (Ky.C. and M.J.T.) read all student responses (69 to 77) and took notes on early thoughts on student interpretation of each of the five CCs. The goal of this phase was to identify key words or sentences that exemplified a student's explanation of a class topic and a CC.

Phase 2. The same two researchers compared their notes in each CC and discussed whether the same idea was reflected in the student responses. When the same idea was reflected in a group of student responses, we created a new code as a category of the similar student responses. We followed the same coding principles regardless of the amount of correctness in a student's response. Whenever student responses presented a faulty assumption or misunderstanding of a biological phenomenon, we created a separate code for those, and differentiated them from the rest of responses. In the cases where a code was disproportionately represented (<3 student responses, excluding the code Blank), we questioned the utility of that code and recoded those responses. After discussing all of our codes

in each CC, 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 specific data set (one class topic), using the early codebook. We compared our findings and resolved disagreements until a consensus was reached. This second iteration of analysis resulted in the final codebook for a given class topic.

Phase 3. In the last phase of this analysis, the same two researchers used the final codebook and independently coded all student responses of a specific class topic. Using the final codebook, a student response to a specific CC could be coded to one or multiple different codes, when appropriate. Double-coded responses refer to those student responses that were coded to two separate codes. We met one final time to discuss any disagreements, reaching resolution in all instances.

Finally, in order to provide extra validation of these findings, a third coder (Ka.C.) analyzed 10% of each data set (student responses in a class topic), achieving kappa values greater than 0.8 for all three data sets. A kappa value was generated by NVivo and measured inter-rater reliability (the extent to which researchers assign the same code to the same student response). A kappa value greater than 0.65 represented good agreement (19).

Analysis considered only the presence or absence of specific codes and not the frequency of a code in a particular student response. In addition, student responses that were illegible, incomplete, or irrelevant to the class topic were assigned the code "Other." Although this code does not have any use for student interpretation, we decided to include it in the results, as an indirect measurement of lack of ability to think about a particular CC. The results present the codes of the final codebook for each class topic, along with the percentages of student responses associated with each code.

RESULTS

Student prior knowledge of the 5CCs

At the start of the semester, we asked students to rank their familiarity with each of the 5CCs on a percentage scale (0 to 100), via an online questionnaire. There was no description provided about the 5CCs, as we did not want to influence their self-reported scores. Results are shown in Fig. 2. Students reported higher familiarity with evolution (EVO; 68%) and structure and function (SF; 61%), followed by pathways of transformation of energy and matter (PTM; 42%), systems (SYS; 37%), and information flow, exchange and storage (IFES; 33%).

Student interpretations of the 5CCs for the topic of aquaporins

Results of thematic analysis of student responses about aquaporins are shown in Table 1. Regarding the CC evolution

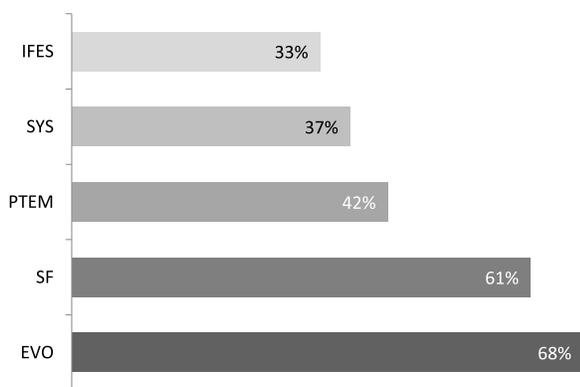


FIG 2. Percentage of self-reported student ($n = 84$) familiarity with the 5CCs.

(EVO), a majority (81%) of students mentioned that aquaporins are one of the most basic structures of living cells or that they have originated from a common ancestor, usually referring to the evolutionary path from prokaryotes to eukaryotes.

In structure and function (SF), 54% of students were able to write something about the structure or the function of aquaporins, with some others (25%) mentioning both structure and function. A very typical response for this CC was “water channel that transfers water” or “protein with hydrophilic and hydrophobic amino acids so the water can pass through.” The phenomenon of water transport was further discussed and explained in the CC information flow, exchange and storage (IFES), when students were asked to describe the type of communication needed during the work of aquaporins. Students (61%) mentioned the action of passive transport and the transfer of water from a higher to a lower concentration (with reference to the cell membrane), also mentioning outside/inside the cell or a concentration gradient. A misconception we noticed in this core concept was the interchangeable use of the terms osmosis and diffusion, although they seemed to understand the from/to movement of water correctly. Confusion between osmosis and diffusion has been seen in high school students learning biology (20), and it is possible that the same misconceptions might persist in first-year students.

In the CC pathways of transformation of energy and matter (PTEM), student responses were similar to those in IFES, with most of them (41%) focusing on water transport. As shown in Table 1, some students (5%) bore the misconception that energy is required for passive transport; however, a greater number (18%) correctly mentioned that no energy is used during the work of aquaporins or the fact that it is a passive transport system (11%). From previous unpublished data, we know that PTEM is a challenging concept for students to grasp and, considering this was the first in-class activity students completed, we chose to accept simple statements as appropriate for the goal of this activity.

In the CC systems (SYS), some students (29%) talked about the phenomenon of osmosis; however, students (40%) listed out the various parts of an “aquaporin system.” The definition of the word “system” varied widely, from responses

listing the fundamental cell membrane elements to responses listing cell components along with its surrounding environment (i.e., concentration gradient). There were also some (12%) students who described the structure of an aquaporin as a “system” of proteins.

Student interpretations of the 5CCs for the topic of aerobic respiration

Aerobic respiration was the first multistep process students had to associate with the 5CCs and the results are shown in Table 2. In EVO, the endosymbiotic theory was the most prevalent student response (43%), describing how prokaryotic mitochondria are absorbed/engulfed into eukaryotes. A few students (13%) elaborated on the fact that aerobic respiration evolved after photosynthesis and the presence of oxygen in the atmosphere. However, there was a large number (41%) of students who were not able to appropriately link what they knew about aerobic respiration to the concept of evolution.

In SF, student responses were either referring to mitochondria (or electron transport chain) as the main location of ATP production (40%), or providing a list of the steps involved in aerobic respiration (20%) and sometimes elaborating on one of the steps. In IFES, students (29%) continued talking about the electron transport chain or redox reactions of NAD^+ and FAD^+ molecules, while some others (17%) listed out the various steps of aerobic respiration or mentioned chemical signaling between proteins (10%). While we consider this variety of student responses very encouraging for linking aerobic respiration to IFES, there was a large student population who tried to elaborate on the genetics of the phenomenon and ended up providing irrelevant responses (code “Other”, 42%). We are not entirely sure whether this happened due to a misinterpretation of the worksheet question, but further modifications of the prompt questions might be necessary.

The CC PTEM received the most relevant responses out of all three data sets, due to the direct association of energy production in respiration. Some (28%) students wrote about production (or use) of ATP or energy in general, while others were more exact in writing that “glucose is turned into ATP, CO_2 and H_2O .” In addition, some (23%) students provided a synopsis of the phases or molecules of aerobic respiration and a few others (22%) described the big picture of aerobic respiration being the cellular process that “breaks food down” to make energy. Similarly in SYS, the most prevalent (63%) type of response was a list of some or all of the main steps of aerobic respiration, perceiving the process of respiration as a biological system.

Student interpretations of the 5CCs for the topic of DNA transcription

DNA transcription was the second multistep process students had to associate with the 5CCs and the results are

TABLE I
Qualitative analysis codebook for the class topic *aquaporins* along with percentages ($n = 77$) of student responses in each code

Code	Description of code (student writes about/a. . .)	Example student response	Percentage of responses ^b	
Evolution (EVO)				
Aquaporins evolved from prokaryote to eukaryote	how eukaryotes have aquaporins after evolving from prokaryotes.	“Since aquaporins are in bacteria, we can say that is one of the most basic structures in life.”	20%	Other 19%; Blank 0%
All living things have aquaporins	the origin of aquaporins from a common ancestor.	“Bacteria, animals, plants, they all have them.”	61%	
Structure and Function (SF)				
Function only	what aquaporins do	“transmembrane protein that allows for osmosis”	27%	Other 21%; Blank 0%
Structure only	about the molecular structure of aquaporins	“must be hydrophobic and hydrophilic in order to be in and out of phospholipid bilayer”	27%	
Both codes [Function only] and [Structure only]		“The protein has to have hydrophobic amino acids and hydrophilic amino acids in order for the water to move through the protein”	25%	
Information Flow, Exchange and Storage (IFES)				
Communication between proteins	how proteins (aquaporins) communicate with one another	“the communication of certain proteins to open and close the channels”	12%	Other 24%; Blank 3%
Transport of water	water molecules being transferred and/or the phenomenon of osmosis	“osmosis, H ₂ O molecule sharing”	61%	
Pathways of Transformation of Energy and Matter (PTEM)				
Energy required	the use of energy by aquaporins	“water is leaving/entering the cell. Requires energy to move through channel”	5%	Other 25%; Blank 0%
No energy required	diffusion, as a no energy mechanism facilitated by aquaporins	“No, water is just passing through”	18%	
Transport of water	the matter, being the water molecules transported	“water is going through”	41%	
Both codes [No energy required] and [Transport of water]		“H ₂ O is being transferred no energy is used”	11%	
Systems (SYS)				
Aquaporin structure	the aquaporin structure, being a system	“a series of polypeptides that differ. . . [.]”	12%	Other 19%; Blank 0%
How the system (osmosis) works	the aquaporins functioning as a system	“Osmosis or/and diffusion”	29%	
List of cell membrane elements	list of cell membrane elements	“water channel, cell membrane”	40%	

^aThe code “Other” indicates incomplete or irrelevant responses to the specific CC and topic.

^bBoldface text indicates the highest percentage of student responses in each CC.

TABLE 2

Qualitative analysis codebook for the class topic *Aerobic respiration* along with percentages ($n = 70$) of student responses in each code

Code	Description of code (student writes about/a. . .)	Example student response	Percentage of response ^b	
Evolution (EVO)				
Evolved after photosynthesis	how aerobic respiration came after photosynthesis	“evolved from the process of photosynthesis, to make use of the oxygen that is being released”	13%	Other 41%; Blank 3%
Endosymbiotic theory	how eukaryotes obtained mitochondria after engulfing prokaryotes	“most [. . .] evolved from prokaryotic cells that combined with other cells to create the double plasma membrane”	43%	
Structure and Function (SF)				
List of steps/elements	list of the input and output of respiration	“need oxygen, H ₂ O and CO ₂ to make ATP”	20%	Other 38%; Blank 2%
Mitochondria structure/function	the characteristics of mitochondria and/or their function	“... small surface area to vol ratios allowed for simple diffusion”	40%	
Information Flow, Exchange and Storage (IFES)				
Communication between proteins	chemical signaling between proteins/enzymes	“communication with the aid of enzymes”	10%	Other 42% ; Blank 2%
List of steps/phases	list of several phases of respiration	“glycolysis, Krebs cycle, electrochemical gradient. . .[]”	17%	
Redox reactions	NADH/FADH molecules	“Protein channels and NADH/FADH carriers take electrons to electron transport chain”	29%	
Pathways of Transformation of Energy and Matter (PTEM)				
Big picture of respiration	food breakdown to produce ATP	“The cell breaks down food in the mitochondria in a long, multistep process that produces 36 ATPs”	22%	Other 8%; Blank 0%
List of phases/elements	list of several phases or cellular elements participating in respiration	“glucose to ATP is glycolysis, Krebs cycle, electron transport chain	23%	
ATP production	ATP being a product of respiration	“energy is being used and produced in all production of ATP”	28%	
Both codes [List of phases/elements] and [ATP production]		“Pathway is the electron transport chain which produces ATP for every glucose molecule”	19%	
Systems (SYS)				
List of elements/structures participating in respiration	list of mitochondrial or cellular structures that facilitate respiration	“matrix, cristae, intermembrane space, plasma membrane”	13%	Other 21%; Blank 3%
List of steps/phases of respiration	list of several phases of respiration	“glycolysis, electron transport chain, Krebs cycle”	63%	

^aThe code “Other” indicates incomplete or irrelevant responses to the specific CC and topic.

^bBoldface text indicates the highest percentage of student responses in each CC.

TABLE 3

Qualitative analysis codebook for the class topic *DNA transcription* along with percentages (*n* = 69) of student responses in each code

Code	Description of code (student writes about/a. . .)	Example student response	Percentage of responses ^b	
Evolution (EVO)				
Central dogma	transcription as part of protein synthesis	“first step in DNA based gene expression”	16%	“Other 42% ; Blank 6%
Common ancestor/Universal codons	origin of DNA code	“The original ancestor must have had it [. . .] It became the universal code for all living things.”	36%	
Structure and Function (SF)				
mRNA/RNA polymerase	the structure of mRNA or function of RNA polymerase	“RNA polymerase enzyme codes base pairs of nucleotides”	9%	Other 40% ; Blank 0%
Big picture of transcription	transcription as a stage of overall gene expression	“DNA is double helix and nucleotide bases are linked up in order to be read (5' to 3') in order to read each codon to make proteins”	13%	
List of molecules participating in transcription	list of transcription molecules	“RNA polymerase synthesizes RNA 5' to 3'”	38%	
Information Flow, Exchange and Storage (IFES)				
List of molecules participating in transcription	list of transcription molecules	“RNA polymerase specific proteins and enzymes help the process go on”	12%	Other 38% ; Blank 0%
Description of transcription phase(s)	a step or phase of transcription	“Proteins are used to split DNA, then mRNA copies the strand”	30%	
Protein synthesis	the connection between transcription and translation	“DNA goes into proteins that give DNA tangible forms, which is caused by DNA transcription”	20%	
Pathways of Transformation of Energy and Matter (PTEM)				
List of molecules participating in transcription	list of transcription molecules	“DNA, mRNA and proteins are made”	11%	Other 28%; Blank 0%
Phase(s) of transcription	one or more transcription phases	“RNA is being produced from DNA”	20%	
Protein synthesis	transcription followed by translation	“A template from DNA is being transcribed into mRNA and mRNA is translated by tRNA into proteins”	41%	
Systems (SYS)				
List of transcription /translation phases	list of transcription or translation phases	“transcription, elongation, translation, initiation”	26%	Other 33%; Blank 3%
List of transcription /translation molecules	list of transcription or translation molecules	“polymerase I, II, mRNA”	38%	

^aThe code “Other” indicates incomplete or irrelevant responses to the specific CC and topic.

^bBoldface text indicates the highest percentage of student responses in each CC.

shown in Table 3. Regarding EVO, some (16%) students referred to central dogma or (36%) the fact that all living organisms have a universal code (passed down from a common ancestor). Similar to aerobic respiration, many (42%) students were not able to provide responses that were clearly related to EVO.

In SF, 38% of the students listed out various molecules taking part in transcription (i.e., DNA, RNA), and sometimes commenting on their structure. For example, a very common response was that “DNA is double stranded” and “RNA is single stranded.” Many (40%) students provided generic descriptions of the topic, such as the goal being the

production of proteins, or that RNA polymerase has a specific structure for its function, nevertheless still making some weak connection to this CC.

In IFES, student responses were mainly divided into two categories: those (30%) describing the phases of transcription and those (20%) describing transcription followed by translation with the goal of protein synthesis. Although the class topic was simply DNA transcription, the tendency to write about translation along with transcription must be attributed to the fact that cellular transcription is usually taught in conjunction with translation when students learn about gene expression. As seen in EVO, many (38%) students could not provide a relevant response to IFES.

In PTEM, the tendency to write about translation after transcription was even greater. Many (41%) students referred to “protein synthesis” or “polypeptides” as the end product of this process. Similarly, in SYS, 38% of students listed out various transcription and translation molecules or the stages/phases of protein synthesis (26%).

DISCUSSION

During a short and simple in-class activity, undergraduate biology students associated what they knew about three previously taught biology topics (aquaporins, aerobic respiration, and DNA transcription) with each of the 5CCs. It is worth noting that the in-class activity of this study did not ask students to provide detailed elaborations, so the term “connections” refers to the brief responses students provided. We consider the connections in student responses as simple associations between biology content and 5CCs definitions, which are superficially made and preliminary to any potential conceptual change (21). We found it was easier for students to make relevant connections of a specific class topic to a specific CC sometimes for simpler phenomena and sometimes for multistep processes, such as aerobic respiration. The differentiation in student ability to better link specific concepts to specific course content could be attributed to their prior knowledge (22, 23). Prior to any in-class activity, a majority of the student population self-reported to be familiar with the CC of evolution (EVO, 68%, Fig. 2) and structure and function (SF, 61%); however, we found that student connections to these CCs were best described within the topic of aquaporins. For the other three CCs (IFES, PTEM, SYS), student familiarity varied, but we still found better connections to some topics compared to the rest. For example, for the CC systems (SYS) and pathways of transformation of energy and matter (PTEM), connections were best described when the class topic was aerobic respiration.

Overall, we saw a tendency to use the given words of the CCs’ titles or prompt questions to write a response. For specific CCs, we found that our prompt questions highly affected the content of student responses. For example, in PTEM, student responses usually included the

“element” that gets transformed during the specific biological phenomenon. Similarly, in IFES, students most often tried to identify the “communication” in the biological phenomenon. Although our prompt questions triggered student thinking to the most probable directions, as presented in this study, they might not have fully captured the relevance of a CC to a biological phenomenon.

Most often, student responses were shorter than a sentence, thus our analysis does not provide a clear indication of student conceptual understanding of class content. On the other hand, these results provide an insight about the fundamental thinking process that introductory biology students engaged in while using the 5CCs, to organize what they have learned about a specific course topic. Although student responses were very specific to the particular topics, the overarching finding of our qualitative analysis is that thinking through the 5CCs contains both, and opposite, tasks of analyzing and synthesizing information.

According to the theory of knowledge integration, as learners add new ideas or facts to their existing knowledge they have to sort through connections in order to start developing a cohesive mental model of a phenomenon (24, 25). The definition of sorting through encompasses the processes of coalescence and differentiation. Coalescence is the process by which two ideas (core concepts of biology) are mutually informed or combined, whereas differentiation is the opposite, i.e., the splitting of an idea into separate elements (25). We see the 5CCs as an organizational framework contributing to a learner’s knowledge integration and improving student expert-like thinking. Using the 5CCs has previously been found to shift the thinking process of nonbiology majors closer to expert-like when participating in a guided (framed) card sorting activity (26).

The effect of using the 5CCs on developing student expert-like thinking becomes less trivial when we consider the absence of student experience with the 5CCs. Students of this study were not lectured on the 5CCs and had not practiced similar activities before. Drawing successful connections between known biological concepts and a molecular biology phenomenon requires acquisition of content knowledge and application of holistic thinking skills (21) that introductory biology students are not expected to have and/or build by themselves. Future research should target student ability to describe the actions and interactions among the parts or phases of a biological phenomenon, in order to have a more nuanced picture of the normative connections (deeper associations) students are able to make between the 5CCs and biology content. Structured assignments could be developed in order to explore potential misinterpretations and misconceptions students have about a phenomenon, before or after teaching. In addition, alternative 5CCs prompt questions need to be examined and validated in multiple introductory biology sections.

Use of teaching practices that incorporate the 5CCs can offer students the opportunity to comprehend, analyze, and synthesize those connections across subdisciplines of

biology. Thus, we suggest that implementing the 5CCs framework into introductory courses could be a way to help students improve their conceptual understanding and holistic way of thinking about biology. Analysis of a biological phenomenon or process into the 5CCs opens up possibilities for knowledge integration by students themselves. We encourage current biology educators to continue adopting teaching approaches that integrate the conceptual framework of the 5CCs and education researchers to keep designing potential assessment tools that could be used to measure undergraduate biology student 5CCs understanding.

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