Research Article

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The Conceptualization of Quantitative Reasoning among Introductory Biology Faculty

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Quantitative reasoning (QR) skills have become a critical competency for undergraduate biology students, and recommendations for curricular reform urge QR training throughout undergraduate biology programs. Much research has been directed at course design, pedagogy, and student challenges in QR, but less research has been directed toward understanding how biology faculty conceptualize the QR skills they are called upon to teach. We conducted in-depth, semistructured interviews with 15 participants teaching introductory biology courses to learn how faculty conceptualize QR at the introductory level. Using phenomenology, responses were coded to establish inductive codes. We found that two themes emerged from the coded conceptualizations: sophisticated, cognitively complex QR skills and basic QR skills. Participants placed emphasis on the more complex QR skills as being important in the undergraduate curriculum, beginning at the introductory level. Participants' conceptualizations of QR aligned with skills called for in curriculum reform, but the perceived notion of "basic" for some skills may not align with the literature. This suggests that more is needed in aligning faculty conceptualization of QR with curriculum, pedagogy, and assessment.

KEYWORDS quantitative reasoning, faculty perspective, introductory biology, *Vision and Change*, BioSkills guide

INTRODUCTION

Recently, there are strong recommendations for biology faculty to teach quantitative skills in their courses (1–3). Such recommendations stem from the surge in the amount and complexity of biological data that has accompanied the rapid advances in computing technology and the increase of biology reliance on quantitative analysis and mathematical reasoning (4). The need for quantitative biology skills is reflected in the rapid growth of research in bioinformatics and genomics and the application of mathematical, statistical, and computational models to systems biology (5). Strasser and Hampton (6) reported that this increase in data wealth has led to an increased need for data analysis and data management skills among biology graduates entering the workforce.

The rise in the quantitative nature of biology in research and industry has thus led to recommendations for curricular and pedagogical reforms at the undergraduate level to develop the quantitative skills of biology students and to apply those skills in biological contexts (1, 7). In 2011, in response to these recommendations, *Vision and Change in Undergraduate Biology Education: A Call to Action* (3) described the need to shift from a vision of undergraduate biology education that relies on memorization of isolated pieces of knowledge to one that focuses on mastering five major core concepts (e.g., evolution, structure, and function) and acquiring six core competencies (e.g., ability to apply the process of science, ability to use quantitative reasoning). The wide agreement that these core concepts and competencies are necessary for developing scientifically literate students encouraged the development of innovative curricular frameworks for undergraduate biology degrees that emphasize these core concepts and competencies (8–10). In response, science education researchers have contributed a wealth of information on course design (11), pedagogy (12), and discussions of student challenges to acquiring core concepts and competencies (13). Clemmons et al. (10) recently elaborated a set of learning outcomes, the BioSkills guide, designed to help biology faculty implement and assess the recommendations of *Vision and Change*. The critical next step is to gain exposure among current faculty to these important ideas for pedagogical change and to determine the extent to which such changes are incorporated into their teaching. However, a review of the literature suggests that research rarely has been

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dedicated to how biology faculty, outside those faculty engaged in discipline-based education research, articulate competencies and how their interpretations inform their teaching. Since the faculty's role is critical in the enactment of any curricular and pedagogical changes (14), we investigated the biology faculty's conceptualizations of quantitative reasoning in the context of undergraduate biology education. Specifically, we interviewed faculty teaching in the introductory biology course sequence, as they are potentially the first to teach quantitative reasoning skills to students transitioning from K-12 instruction.

In essence, *Vision and Change* called for opportunities for students to practice science and not just recall scientific knowledge from readings. To understand the nature and development of scientific knowledge, we must understand the epistemic practices of scientists (15–17). Based on this understanding, *Vision and Change* included recommendations for curricular and pedagogical changes in undergraduate biology. In terms of curricular changes, there is a need to incorporate scientific practices (e.g., constructing scientific knowledge through experimental design, making decisions about data collection, analysis, and communication) into the curriculum (15). Science learning environments that allow students to model the epistemic practices of scientists promote student engagement, promote a better understanding of scientific concepts (18), and show promise in preparing biology students to enter the workforce. For example, Sadler and McKinney (19) studied how the use of authentic research experiences that highlighted epistemic practices (such as students' active involvement in the collection, quantification, and analysis of data) affected undergraduate science students' learning outcomes. They found that these experiences facilitated students' understanding of the nature of science (NOS) and improved attitudes toward science and self-efficacy. Similarly, Hanauer et al. (20) found that project ownership increased students' sense of agency and achievement, resulting in increased retention in the sciences; Hanauer and Dolan (21) subsequently developed and evaluated a project ownership survey (POS) to measure the effectiveness of student research experiences on the psychosocial and cognitive facets of this pedagogical element.

Among the skills called for in *Vision and Change* are the ability to apply the process of science, including hypothesis testing and data interpretation, and the ability to use quantitative reasoning (QR). Biologists rely on QR as a crucial epistemic practice to generate research questions, analyze and interpret data, and develop models (4). Despite clearly articulated needs for QR proficiency for biologists entering the workforce (22), instruction in these QR skills is often lacking or underdeveloped in undergraduate biology education. Students often take mathematics and biology courses in near independence (23, 24) and rarely experience mathematics within the context of their own discipline (11). Moreover, students often do not understand the importance of integrating QR into their biology courses, a limitation that could follow them into their professional careers (24). Despite a lack of evidence that biology students are math-averse (25), some students who perceive themselves as math-weak gravitate toward biology due to the perception that biology does not rely on mathematics (11, 26). Faculty sometimes shield their students from the quantitative aspects of biology (5), although exposing students to QR at the start of their academic career is known to foster their quantitative competency in a biological context (11). Matthews et al. (27) provided strong evidence that biology students need to see, acknowledge, and then understand how important it is for them to develop QR skills during their undergraduate studies and points to the need to encourage biology faculty to integrate QR into all levels of student learning. Students who feel, or develop, a level of satisfaction with math early in their undergraduate training may retain that attitude; using an Attitudes toward the Subject of Mathematics Inventory (ASMI), Wachsmuth et al. (26) found that math attitudes may be malleable if students can frame mathematical work contextually as having utility or relevance. It may also be necessary to explicitly help undergraduates put mathematics into biological contexts; Beck (28) found that implicit teaching of statistical and quantitative concepts did not improve QR and making explicit links between mathematics and biology may be necessary, at least at introductory levels.

While most biology faculty are trained in and employ QR in their research (29), they face challenges to bring quantitative skills (e.g., reasoning, modeling, statistical analyses) into their teaching. Faculty may not recognize the need to integrate QR with the science content of their courses, may lack the pedagogical content knowledge needed to teach QR effectively (30), or may lack the confidence to bring more quantitative skills to their curriculum (13, 31). To integrate QR into their courses, biology instructors could benefit from clearly articulated guidelines and informed resources (e.g., reference 32). *Vision and Change* (3), although calling for QR instruction, largely left to individual faculty to determine what such instruction looks like. Subsequent to *Vision and Change* (3), Clemmons et al. (10) expanded the six core competencies into the BioSkills guide of measurable learning outcomes. Prior to publication of the BioSkills guide, faculty who might implement QR in their courses usually relied on their individual experience and conceptualization of QR to inform their course content. This assertion also leaves out biology faculty who are not well-versed in discipline-based educational research (DBER) and may not have knowledge of *Vision and Change* and the related tools and resources. An integrated understanding of how biology faculty conceptualize QR in their courses would help inform curricular and pedagogical development moving forward.

A comprehensive body of work has been published on "how to" incorporate authentic QR as epistemic practice in biology courses (e.g., references 31 and 33) and the challenges students face in developing QR skills (34). Less is known about how biology faculty conceptualize QR and how they provide instruction to their students. Most biology faculty have experience with QR as research scientists, but they may lack the pedagogical content knowledge (35) for teaching QR (36). This may be especially true of research-focused faculty who may not be as familiar with

DBER as their education-focused colleagues (36). To provide successful resources to help faculty implement curricular change, it is necessary to create a loop; we must first understand how diverse faculty stakeholders conceptualize QR, and then we can work to develop curriculum resources that help guide them in their efforts to teach QR. To that end, our research seeks to explore how faculty in introductory biology courses understand and conceptualize the term "quantitative reasoning" (QR). We intentionally chose the introductory biology focus, as studies (11, 23) suggest that students should be exposed early and often to QR practices to improve skills and self-efficacy in a biological context. Our work was focused on two research questions. (i) How do faculty in introductory biology courses conceptualize QR? (ii) Do those conceptualizations vary with faculty research background, teaching experience, or institution type?

METHODS

This study was a qualitative exploratory study to understand the conceptualization of quantitative reasoning (QR) by faculty teaching introductory biology courses. We interviewed 15 biology faculty, from 14 biology departments at New England universities and colleges (Table 1). Phenomenological design suggests interviews of 5 to 25 participants (37) to understand the essence of experience, so we selected a participant pool of intermediate size.

Participants

We identified 14 universities and colleges in New England which represented five Carnegie classifications (http://carnegieclassifications.iu.edu/). We utilized a snowball sampling method (38) to recruit department chairs, who then recruited participants for interviews. We submitted email messages to department chairs asking for referral to faculty members who most recently were assigned to teach in the introductory biology course sequence. The time limitation was included to alleviate potential selection bias of department chairs. After the faculty were identified, we sent an informed consent letter describing the research, along with the interview questions. Once the participants communicated their willingness to take part in the study, an interview was scheduled at the available times provided by the faculty. Faculty were identified by their primary research interest. Their primary research interest was then categorized by subject area as either cellular/molecular biology or ecology/evolutionary biology, the two major subject areas of introductory biology. Because faculty were identified by their department chairs for participation, we did not attempt to have equal numbers of faculty in each subject area category. Descriptor data were also collected on faculty rank and years of teaching. All participants were deidentified by use of a pseudonym. Three research groupings were constructed (Table 1): (i) subject area focus in biology (cellular/molecular, ecology/evolutionary), (ii) years of teaching experience (0 to 4 yr, 5 to 9 yr, 10 to 14 yr, 20+ yr), and (iii) Carnegie classification (http://carnegieclassifications.iu.edu/). There are no known safety concerns with this study because it did not contain any laboratory components.

Interview protocol

The interview questions (Appendix 1) were drafted by the first two authors and then revised after receiving feedback from two science education research groups and two pilot implementations. Semistructured, responsive interviews, a qualitative research tool of one-on-one interviews (39), were conducted via videoconference; all interviews were conducted by the first author. Interviews took ∼45 min and consisted of four sections: (i) introductory questions on course content and teaching experience, (ii) conceptualizing QR, (iii) background and interests in QR, and (iv) implementing QR. This paper reports the findings of the second interview section: conceptualizing QR. Participants consented to having the interviews recorded and transcribed for data analysis.

Data analysis

For each interview, statements in response to questions regarding conceptualization of QR were coded (see below); where appropriate, an individual statement would be assigned multiple codes. The data analysis was informed by the interview questions, QR definitions in educational research (e.g., references 40–42), and the *Vision and Change* (3) document. These artifacts helped deductively frame the initial and overarching codes such as "Meaning of QR" and "Faculty Background in QR." As suggested by the phenomenological data analysis approach, we utilized "horizontalization" highlighting significant statements across interviews to help us understand the essence of the teaching QR experience. We then articulated "clusters of meaning" that helped us formulate codes representing the highlighting statements (e.g., conceptual sensemaking through data, creating/describing graphical data). The goal of developing the codes representing such clusters of meaning was to capture participants' experiences leading to their definition of QR in introductory biology courses. This process is called "bracketing" (43) and helps researchers remove their knowledge or experience from the essence of the phenomena as much as possible. Two researchers (authors 1 and 2) were involved in developing the coding framework and then coding the interviews. Initially, we independently coded 4 of the 15 interviews for the initial phase of establishing a reliable coding framework; we used the percent agreement (P_A) formula (44) to calculate the intercoder reliability for each code. At this initial phase, the percent agreement for each code ranged between 72 and 100%. We decided to remove or collate the codes that were rated below 90% (45), e.g.,

TABLE 1

Participant information relating to 15 faculty who teach in the introductory biology course sequence who participated in ethnographic interviews relating to the teaching of quantitative reasoning (QR); faculty were drawn from universities and colleges in the 6 New England states

Participant pseudonym	Yrs of Teaching	Faculty rank	Carnegie classification[a]	Research area	Subject area focus	Familiarity with *Vision and Change*
Barbara	10	Assistant professor	Baccalaureate - arts/science	Immunology	Cellular/molecular	No
Betsy	2	Lecturer	M2	Cancer biology	Cellular/molecular	Yes
Bruce	5	Assistant professor	R2	Marine biology	Ecology/evolution	Yes
Carolee	6	Senior lecturer	R1	Entomology	Ecology/evolution	Yes
Cindy	3	Assistant professor	Baccalaureate - diverse	Microbiology	Cellular/molecular	No
David	26	Senior instructor	Baccalaureate - arts/science	Plant ecology	Ecology/evolution	No
Don	33	Professor	M3	Plant biology	Ecology/evolution	Heard of it
George	5	Assistant professor	R1	Plankton ecology	Ecology/evolution	No
Jim	33	Principle lecturer	Baccalaureate - arts/science	Wildlife ecology	Ecology/evolution	Heard of it
Ken	41	Professor	R1	Marine ecology	Ecology/evolution	No
Lynda	9	Associate professor	M1	Microbiology	Cellular/molecular	No
Maryann	3	Assistant professor	M1	Plant evolution	Ecology/evolution	Yes
Melinda	3	Assistant professor	R1	Plant ecology	Ecology/evolution	Yes
Paul	22	Professor	Baccalaureate - diverse	Plant ecology	Ecology/evolution	No
Whitney	2	Lecturer	R2	Environmental science	Ecology/evolution	Yes

[a] Carnegie classifications: R1, doctoral universities, very high research activity; R2, doctoral universities, high research activity; M1, master's colleges and universities, larger programs (200+ degrees); M2, master's colleges and universities, medium programs (100 to 199 degrees); M3, master's colleges and universities, smaller programs (50 to 99 degrees); baccalaureate colleges - arts and sciences; baccalaureate colleges - diverse fields.

"using graphical models" and "using mathematical models" were collated as "using models." While coding the rest of the interviews, we went through the iterative process of discussing, revising, and defining the remaining codes until we reached 100% agreement (46). Individual statements, as opposed to entire responses to a question, were coded for each participant. In instances where two or more codes could be applied to a singular statement, cooccurrence of codes was noted. Once the coding framework was established, the lead author of this study conducted final revisions of all codes for all interviews. The inductive codes provided in-depth qualitative accounts of how introductory biology faculty conceptualize QR. Coding analysis was done through Dedoose version 7.0.23, a qualitative research analysis tool (www.dedoose.com). Once we determined the codes, our final step of the phenomenological approach was to see whether there were common themes in how participants explained each QR skill. This study will focus specifically on the overarching code of "meaning of QR" and the related inductive codes in order to respond to the research questions.

RESULTS

Faculty conceptualization of the meaning of quantitative reasoning

Although we cannot make any generalizable claims about relationships between faculty conceptualizations of QR and their attributes due to the small participant number and the nature of this study, we can highlight some patterns that we noticed in our data, which can be useful for further investigation. When we asked participants to define QR in the context of their teaching, nine codes emerged. When we looked at the qualitative excerpts for these codes, we noticed that faculty's descriptions for these nine codes used keywords such as "simple," "easy," "not difficult/difficult," and "challenging." These keywords led to two thematic areas: sophisticated and basic QR skills. The first theme included references to what participants saw as sophisticated, cognitively complex QR skills related to how students should "think about data" (Table 2, Table S2). Participants often described these skills as potentially difficult for introductory biology students. The second theme included references to what participants described as the more basic QR skills of what students should do with data (Table 3, Table S3), often suggesting that students should already possess these skills when they enroll in the course. Participants conceptualized "doing with data" as skills where students might work with data without recognizing the meaning or context of what they are doing. For example, participants spoke of students entering numbers into a formula to obtain a correct answer but not knowing what that answer meant. Similarly, students might successfully generate a graph with data means and measures of variation but not understand what the variation indicates about the data. It is important to note that these codes were generated wholly from participant comments and do not necessarily reflect what is known from the literature. Indeed, some participants viewed certain skills as basic (e.g., "creating/describing graphical data"), while literature (e.g., references 47 and 48) suggests that they are complex.

First theme: sophisticated, cognitively complex QR skills. Based on the wordings that the participants used, we identified that five QR skills were conceptualized as being sophisticated and cognitively complex. All participants emphasized at least one of these five skills in their conceptualization of QR. The following five codes of skills that were grouped under this theme are in accord with the array of critical thinking skills called for in *Vision and Change* (and others). Codes are presented in the order from most to least applied.

(i) Conceptual sensemaking through data (12 of 15 participants). This code was represented the most in the transcripts. Excerpts that were grouped under this code referred to the ability to analyze or interpret data to better understand a concept, to extract evidence-based meaning from a figure, or to create a figure that graphically demonstrated a concept. For example, Paul, an ecologist/evolutionary biologist, described a lesson where he provided data on the relationship between leaf size and climate and expected the students to be able "to look at conceptual problems and turn them into mathematical models, calculations, analysis, etc." For Paul, students should be able to draw a trend from interpretation of global data and to conceptually make sense of the factors affecting the leaf size across different climate zones. We saw a higher ratio of ecologists/evolutionary biologists highlighting conceptual sensemaking through data compared to that of cellular/molecular biologists (10 of 11, 2 of 4, respectively). We also noticed that ecologists/evolutionary biologists would elaborate on conceptual sensemaking with examples from specific topics, such as population growth, habitat characteristics, and prey behavior. On the other hand, cellular/molecular biologists talked about conceptual sensemaking more generally. Barbara, a cellular/molecular biologist, spoke in generalities of students being able "to look at a set of numbers and extract what it means," but she did not offer an example in context. Emphasis on conceptual sensemaking through data was stressed by participants across all teaching experience categories and Carnegie classifications (Tables S3 and S4).

(ii) Using models (8 of 15 participants). This code was conceptualized as the ability to understand and/or create a model to represent data or evidence. Models that participants referred to could be conceptual, mathematical, or graphical. For example, Betsy, a cellular/molecular biologist, talked of having students employ the numerical Hardy-Weinberg model "to take a written-out series of sentences and apply the formula" to calculate gene frequencies. Paul, an ecologist/evolutionary biologist, when teaching students to use a mathematical model of the interaction between wolf and moose populations, said that QR ". . . involves

TABLE 2

Theme 1: sophisticated QR skills[a]

Code name	No. of participants	Brief explanation of code	Example excerpt(s)
Conceptual sensemaking through data	12 (2, 10)	Working with data to better understand a concept, to extract conceptual meaning from a figure, or to create a figure that graphically demonstrates a concept	"I think a little bit more broadly about quantitative reasoning as the ability of the students to be able to take some of the concepts and the concrete information that they've learned in class, and be able to apply it to some sort of problem to answer questions, analyze data." (Lynda, c/m)
Using models	8 (2, 6)	Understanding/creating a model (conceptual, graphical, numerical) to represent data or evidence as a facet of QR	"[QR is] the ability to use, and apply, and understand mathematical models to understand natural situations and the world around us" (Betsy, c/m)
			"So being able to understand the Hardy-Weinberg Equilibrium [a mathematical model] and applying it to a problem and understand the outcome is sort of that baseline level [of understanding modeling], but then there's the higher level of being able to think numerically and understand that what's happening in the world around us can be represented in an equation, or in a formula, or change can be modeled out." (Carolee, e/e)
Thinking in numbers	7 (2, 5)	"Doing math" in one's head, e.g., 10% of a sample of 73 trees would be close to 7 and not 3 trees	"What I'll have them do is sometimes look at an equation, and they have to be able to kind of interpret it not just as numbers, but as kinda like what—how different variables can affect each other, so I don't do this a lot 'cause there's not a lot of places to put this in. But thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using—so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way." (Melinda, e/e)
Applying comparative/ inferential statistics	7 (2, 5)	Applying statistical tools to support hypothesis testing, including the use of tools such as *t* tests, analysis of variance (ANOVA), and correlation/ regression.	"[I see QR as] how to interpret data and do hypothesis testing with statistical tests . . . and that's [descriptive statistics] not as important as understanding sampling or—and variability [in data] and understand that in science, we can falsify hypotheses, but we can't really prove hypotheses. . . . And how you can look at two means that are different, but that difference may not mean anything in biology." (Jim, e/e)
Using inferential intuition	4 (1, 3)	Drawing key scientific ideas by looking for trends or patterns in a data set without having to do calculations	"The intuition about data and numbers. . .So I think there's kind of like this tug of war situation where . . . intuition is going to be something that lends itself to quantitative reasoning, and strong quantitative reasoning skills." (Cindy, c/m)

[a] Codes for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed: 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Numbers in parentheses in the participant column represent the number of cellular/molecular biologists and ecologists/evolutionary biologists to which the code was reported, respectively.

TABLE 3
Theme 2: basic QR skills[a]

Code name	No. of participants	Brief explanation of code with example excerpts	Example excerpt
Creating/describing graphical data	8 (3, 5)	Identifying independent and dependent axes, units of measure, and numerical data, e.g., mean, standard deviation, regression line	"So, basically it [QR] means that they [students] can look at a set of numbers and extrapolate what it means. So, you can look at a graph and you can read the graph and understand what it means. . . . But if you can look at a graph and you can look at in a way that—you can clearly look at it to see if the axis makes sense, and what the person is saying about the graph actually is what the data represents. That being in a major quantitative reasoning." (Barbara, c/m)
Organizing data	5 (2, 3)	Organizing information or messy data sets into a useful or meaningful form	"[QR is] the ability to understand what data means and how to organize data so that it makes sense. . .And then again, how are you going to organize that information into some useful form that has summarized things quickly so that people can understand what it is that you're talking about." (Lynda, c/m)
Using descriptive statistics	2 (1, 1)	Identifying measures of central tendency and variation	"So we start out with descriptive statistics . . . So before they even learn what biology is, they learn that when we have to have a look at the world, we observe it, . . . and we quantify what we're seeing . . . We're analyzing the data we got. And so they're doing descriptive statistics. What is the mean? What does that mean? The central tendency of the data. What is the standard deviation? It's a measure of variance. And it's how wide this histogram is at a certain place. So we're trying to get the idea that data are not perfect, that there's variance in the data, and that we have to make decisions based on how the mean and the standard deviation reflect each other." (Don, e/e)
Making measurements	2 (0, 2)	Attributing a unit measurement to an object or observation	"I think the [QR] skills around some of their [experimental] designs revolve around getting comfortable with both the tools and the types of measurements that are appropriate for particular experiments for what we do in the lab. So the tools being the hydrometers that they build, how did they scale things properly, what are they measuring and have they measured it properly with the appropriate equipment." (Whitney, e/e)

[a] Codes for participant conceptualization of quantitative reasoning (QR). Fifteen participants were interviewed: 4 cellular/molecular biologists and 11 ecologists/evolutionary biologists. Numbers in parentheses in the participant column represent the number of cellular/molecular biologists and ecologists/evolutionary biologists to which the code was reported, respectively.

quantitative reasoning and models . . . to make quantitative predictions conceptually and qualitatively." He also spoke of using a graphical model of the intermediate disturbance hypothesis "to [have students] look at a graphical representation of it and understand the concepts behind it." It is important to note that participants viewed creating or using graphical models as a sophisticated skill but, paradoxically (see below), viewed the creation of a graph from a data set as a basic skill. Both ecologists/evolutionary biologists (6 of 11) and cellular/molecular biologists (2 of 4) emphasized using models, but cellular/molecular biologists emphasized graphical models over numerical models, and ecologists/evolutionary biologists emphasized them equally. Emphasis on using models was stressed by participants across all teaching experience categories and Carnegie classifications (Tables S3 and S4).

(iii) Thinking in numbers (7 of 15 participants). No participant employed the definitive term "numeracy" often used in the literature, but two participants specifically spoke of thinking in numbers; we thus employed the term as being representative of participant experience. Under this code, we grouped excerpts in which participants referred to students' ability or inability to perform simple mathematical operations in their heads. Students who demonstrate this skill understand relative percentages, orders of magnitude, and exponential functions. Betsy, when describing how some students lack the ability to think in numbers, said "they come up with some totally unreasonable answer [on their calculator and] do [not] realize that it's an unreasonable answer." Ecologists/evolutionary biologists and cellular/molecular biologists emphasized this ability equally (5 of 11, 2 of 4, respectively). Thinking in numbers was coded by participants in all teaching experience categories and Carnegie classifications (Tables S3 and S4).

(iv) Applying comparative/inferential statistics (7 of 15 participants). Excerpts under this code included references to the ability to go beyond the descriptive statistics (e.g., mean, standard deviation) to use comparative/inferential statistics in data analysis and interpretation and to support hypothesis testing. Jim, an ecologist/evolutionary biologist, said "I tend to want students to learn how to interpret data and do hypothesis testing with statistical tests." Both ecologists/evolutionary biologists (5 of 11) and cellular/molecular biologists (2 of 4) emphasized hypothesis testing, but the two cellular/molecular biologists were explicit in using hypothesis testing to specifically determine statistical significance. Barbara, a cellular/molecular biologist, teaches Mendelian genetics by having students rear fruit flies; they test the hypothesis that expected and observed frequencies align and determine "is it statistically what we expect?" This code was not applied to participants in the 5 to 9 year teaching category or from participants in R2 institutions (Tables S3 and S4).

(v) Using intuition (4 of 15 participants). When used in the context of QR, intuition is the act of predicting trends in a data set, the ability to understand quantitative evidence conceptually, and the ability to draw together disparate evidence or ideas to generate claims or hypotheses. Ken, an ecologist/evolutionary biologist, spoke of the ability to intuit a pattern in nature (e.g., organisms occupy predictable areas within an intertidal zone) and to develop a testable hypothesis to verify that pattern. He indicated that students intuit that the cause of zonation is tidal exposure because they "think about the biology first . . . [and then] set things up to test [a hypothesis]." Betsy, a cellular/molecular biologist, spoke about an intuitive understanding of what one unit of pH change means, "Let's talk about how to understand this more intuitively [in terms of magnitude]," indicating that students can perceive that one unit of pH change is a 10-fold change in hydrogen ion concentration. Participants for whom this code was applied were either early- (0 to 4 years) or late-career (20+ years) educators (Tables S3 and S4), with one participant each from all Carnegie classifications except R2.

Second theme: basic QR skills. The second theme of QR conceptualization related to what participants described as more basic skills of how students collect, organize, and process data; the following four codes thus relate to what students do with data. Codes are presented in the order from most to least applied.

(i) Creating/describing graphical data (8 of 15 participants). This code was the only basic QR code that was recorded frequently by both populations (5 of 11 ecologists/evolutionary biologists, 3 of 4 cellular/molecular biologists) and was conceptualized as the ability of students to correctly identify independent and dependent axes, units of measure, and numerical data (e.g., mean, standard deviation, regression line). Participants were clear in distinguishing this skill from conceptual sensemaking through data and using models, although research (www.dedoose.com) (47, 48) finds that this is not uniformly a basic skill. Don, an ecologist/evolutionary biologist, gave the following example as an in-class exercise, where "We pool the whole course data together [and] plot those out on scatterplots . . . [to produce] seven graphs and three tables." He then goes on to describe the output as "publishable-quality . . . meeting legibility standards in Excel and Word." Barbara, a cellular/molecular biologist, indicated that students "can read a basic graph" and describe what is being measured and the relationship between the variables. Creating/describing graphical data was the only basic QR skill that was recorded frequently. This code was equally emphasized by all teaching experience categories but did not appear in R2 or baccalaureate - diverse institutions (Tables S3 and S4).

(ii) Organizing data (5 of 15 participants). QR under this code was conceptualized as a student skill in organizing information or messy data sets into a useful or meaningful form; the importance of this QR skill is reinforced in the literature (17, 49). Lynda, a cellular/molecular biologist, spoke about the importance of organizing data to communicate information: "How are [students] going to organize that information into some useful form . . . so that people can understand what it is that [they are] talking about." We noted that participants linked the importance of organizing data, in either graphical or tabular form, to communication or explanation. This code was used by both ecologists/evolutionary biologists (3 of 11) and cellular/molecular biologists (2 of 4) across most teaching experience categories but only from master's and baccalaureate - arts and sciences Carnegie classifications (Tables S3 and S4).

(iii) Using descriptive statistics (2 of 15 participants). This code was characterized by measures of central tendency and variation. The two participants indicated that the ability to calculate these measures and the ability to understand how these measures characterize data were both important pieces of the meaning of QR. For example, Betsy, a cellular/molecular biologist (0 to 4 year, master's), stressed the importance of descriptive statistics to understand data: "[The students] do averages [and] standard deviations . . . to understand what does standard deviation mean?" David, an ecologist/evolutionary biologist (20+ years, baccalaureate - arts and sciences), echoed the importance of descriptive statistics to communicate "measures of location, measures of variability, . . . in a meaningful pictorial way that's going to tell that story." It was interesting to note that only two participants explicitly recorded using descriptive statistics, as this is a QR skill that most all scientists rely on.

(iv) Making measurements (2 of 15 participants). This code was noted as a QR skill by two of the participants, both ecologists/evolutionary biologists. As defined by Thompson (50), making measurements can be considered the mathematical process of attributing a unit measurement to an object. Don (20+ years, baccalaureate - arts and sciences) stressed the importance of measurements to provide evidence for patterns that students might be seeing: "We can measure it, so that we're not just seeing what we think we see but quantifying how much." Whitney (0 to 4 years, R2) stressed that students should know that they are measuring attributes and not measuring "data." She noted, "Are you measuring the data? [No] you [are] measuring the size, the length, the circumference, the diameter." Whitney was the only participant to mention qualitative data in her conceptualization of QR, as she pointed out "that not all data can be measured . . .. Think about the . . . results in terms of numbers versus in terms of shapes or colors, or smell or texture."

Code cooccurrence. To determine any relationships between the ways that the QR skills were conceptualized by participants, transcripts were analyzed for code cooccurrence within excerpts (Table 4). A code cooccurrence appears in a statement when the same participant talks about different codes in explaining the meaning of QR. Code cooccurrence among the sophisticated, cognitively complex skills was revealed in 42 transcript excerpts, whereas code cooccurrence among basic skills was seen only twice. Code cooccurrence bridging the two themes (i.e., sophisticated cooccurring with basic) was revealed 14 times. For example, this first excerpt from Melinda (ecologist/evolutionary biologist) was coded as creating/describing graphical data and conceptual sensemaking through data:

> [QR] is interpreting—actually, interpreting tables and graphs . . . being able to read the table or graph, understand it, and then being able to say, "Okay, based on like the fact that, you know, this is larger than this in the graph, right, then I think that the hypothesis is supported, or I think that hypothesis is not," [to] look at an equation, and be able to kind of interpret it not just as numbers, but as kinda like what—how different variables can affect each other. . .

A second excerpt from Melinda was coded as thinking in numbers and using models:

> . . .thinking about like, well, if you increased, you know, this variable that's on one side of the equation, how would it affect, you know, your output variable. So it was kind of using—so it's, again, reasoning with numbers, right, thinking about how changes in one variable affects changes in others in kind of this numerical way.

Faculty attributes and the variation in the meaning of QR

Our second research question examined whether QR conceptualizations varied with faculty research background, teaching experience, or institution type. We found that participants in both cellular/molecular biology and ecology/evolutionary biology similarly conceptualized QR in terms of sophisticated higher-level skills. Both groups also more heavily emphasized sophisticated higher-level skills (theme 1) over basic skills (theme 2). Participant QR conceptualization, based on years of teaching experience, similarly showed a focus on the sophisticated higher-level skills. It was interesting to note that both early-career educators (0 to 4 yr) and those with over 20 years of teaching experience had all nine codes applied to their transcripts, suggesting strong agreement in QR conceptualization between these two groups. The four references to intuition (Table 2 for research focus) were made by faculty who either were in their first 5 years of teaching (1 participant) or with more than 20 years of teaching experience (3 participants). While less commonly reported overall, participant conceptualization of basic QR skills did appear across all categories of teaching experience.

We found that, for the most part, all categories of Carnegie classifications stressed theme 1, the sophisticated higher-level skills of QR, which may suggest upon the collection of further supporting evidence that baccalaureate-granting institutions conceptualize QR in much the same way as institutions with graduate-level programs. Also of note is that participants at R1 and R2 institutions were less likely to use the basic-level skills codes. For example, neither organizing data nor using descriptive statistics was applied to R1 or R2 transcripts.

DISCUSSION

Our research provides insight into the QR conceptualization of biology faculty who teach introductory biology

TABLE 4

Two code cooccurrences between nine child codes representing participant conceptualization of quantitative reasoning (QR)[a]

	No. of cooccurrences for:								
	Theme 1: sophisticated QR skills					**Theme 2: basic QR skills**			
No. of cooccurrences for:	**Conceptual sensemaking through data**	**Using models**	**Thinking in numbers**	**Applying comparative inferential statistics**	**Using intuition**	**Creating describing graphical data**	**Organizing data**	**Using d escriptive statistics**	**Making measurements**
Theme 1									
Conceptual sensemaking through data		7[b]	11[b]	6[b]	7[b]	4	3	1	1
Using models			2[b]	1[b]	4[b]	2	0	0	0
Thinking in numbers				2[b]	0[b]	0	0	0	1
Applying comparative inferential statistics					2[b]	1	0	0	1
Using intuition						0	0	0	0
Theme 2									
Creating describing graphical data							**0**[c]	**1**[c]	**0**[c]
Organizing data								**1**[c]	**0**[c]
Using descriptive statistics									**0**[c]
Making measurements									

[a] Fifteen participant interviews were coded for responses; where appropriate, an individual statement could be assigned multiple codes, which is represented in the table. The numbers in the table represent the number of times two codes cooccurred and not the number of participants for whom cooccurrences were recorded.

[b] Cells with the same letter footnote indicate where skills within the same theme are cooccurring.

[c] Cells with the same letter footnote indicate where skills within the same theme are cooccurring.

courses. This insight could suggest recommendations for curricular and pedagogical changes. Research in biology education has already indicated that students with strong QR skills feel more ready for their future careers (27). The semistructured nature of the responsive interviews allowed us to develop a richer understanding of QR conceptualization that can be instrumental in developing larger survey-based studies. Faculty play a pivotal role in providing experiences for biology students to improve these skills. By interviewing faculty teaching in introductory biology courses, we were able to distinguish two themes of conceptualization that can inform pedagogy at the initial stages of a biology curriculum and provide scaffolding for development of increasingly sophisticated QR skills as students move through their academic programs.

Faculty conceptualization of the meaning of quantitative reasoning

Participant conceptualization of QR revealed nine codes emerging, which we grouped under two themes: (i) the more frequently recorded theme of sophisticated, cognitively complex skills and (ii) the less frequently recorded theme of basic skills. This may represent participants' own experience as biological researchers with the epistemic practice of their scientific field. In research, these faculty must employ cognitively demanding QR skills as they develop research questions, conduct and analyze their data, and prepare their data for dissemination to a scientific audience. While they also employ the more basic skills, e.g., organizing data and preparing graphs and tables, they are perhaps so accustomed to these practices as second nature that these skills may come less to mind when they are asked to conceptualize QR for undergraduate levels. Students may still possess naive epistemologies, which can affect their ability to interpret complex information, and they may view certain QR practices as more cognitively demanding than their faculty do. Hoskins et al. (51) designed the C.R.E.A.T.E. approach to primary literature as a pedagogical tool which helps students "think like a scientist" in tasks such as graphing. diSessa (52) argues that some of these practices, such as graphing, are taught only as "sanctioned representations," which simplifies how these representations are constructed by scientists. While our participants view graphing as a skill, researchers argue that graphing is more than a cognitive skill but a practice that involves social dimensions of scientists' work when they improve, communicate, and reflect on the knowledge produced in their field (53). Our participants may also possess an "expert blind spot" (54) where their domain-specific knowledge of how to create and/or interpret graphs makes them blind to the processes of their novice students. Participants have acquired domain-specific knowledge, they have long-term practices in their respective disciplines, and they may be able to exploit their knowledge of familiar experiences to new tasks (54). Moreover, Shah et al. (55) have shown that graph complexity can affect students' graph comprehension, and participants may have been "expert blind" to the fact that they possess greater topic familiarity and graphical literacy than do their students. Both of these factors influence top-down knowledge of graph comprehension because perceptions are heavily influenced by expectations and prior knowledge. For undergraduate students to understand how scientists in biology use graphing, we need to aim for a deeper understanding of graphing practices. For such deeper understanding, our students need to experience "metarepresentational" components of graphing, including "critiquing and evaluating" the adequacy of graphs and creating new ones that better represent the data and their context (52).

It is interesting to note that participant conceptualization of QR was not confined to any single skill outlined in either *Vision and Change* or the Bioskills Guide (10); rather, the conceptualizations integrated multiple skills from those documents. Specifically, *Vision and Change* defined three individual core competencies relating to QR (ability to apply the process of science, ability to use quantitative reasoning, and ability to use modeling and simulations), and the BioSkills guide provided three comprehensive learning outcomes aligned with QR (modeling, quantitative reasoning, and process of science). Whereas *Vision and Change* does not specifically provide learning outcomes, the Bioskills guide elaborates on program- and course-level learning outcomes, providing an additional tool to compare participants' experience and conceptualization of QR, which aligns well with our study. For example, the three program-level learning outcomes under the BioSkill modeling (purpose of models, model application, models) align well with conceptual sensemaking through data and using models.

In some cases, in our classification, one BioSkill learning outcome was grouped under two themes. For example, the program-level learning outcome of numeracy (under the BioSkill quantitative reasoning) has course-level learning outcomes that were grouped under both sophisticated and basic themes for our participants. One course-level learning outcome, "Use rough estimates informed by biological knowledge to check quantitative work" (10), that was classified under numeracy aligns with our sophisticated skill thinking in numbers, whereas "Perform basic calculations (e.g., percentages, frequencies, rates, means)" (10), another outcome under numeracy, aligns with the basic skill of using descriptive statistics. Similarly, the program-level learning outcome of quantitative and computational data analysis, under the BioSkill quantitative reasoning, has course-level learning outcomes that distribute across our two themes. The BioSkill "Select, carry out, and interpret statistical analyses" (10) is equivalent to applying comparative/inferential statistics, whereas "Record, organize, and annotate simple data sets" (10) aligns with organizing data. Lastly, the BioSkill process of science is represented in our participants' conceptualization by conceptual sensemaking through data and applying comparative/inferential statistics; both of these sophisticated skills align well with several of the course-level learning outcomes found in the program-level outcome of data interpretation and evaluation.

An important finding of this work is that conceptualization of QR by our participants, who represent diverse research areas, teaching experience, institutional backgrounds, and knowledge of discipline-based education research, does not necessarily align with the literature. While most participants were in agreement with the sophisticated skills of QR, they clearly separated understanding graphical models from creating graphical data. The weaknesses in graphing abilities at the undergraduate level, and persistence of common graphing errors among students, suggests that current curricula are ineffective at helping students access and understand graphical data (56). Harsh and Schmitt-Harsh (56) assert that students are often taught graphing skills with "clean" or "simple" data that obscure the messiness inherent in sample variability and subtle relationships between variables. Schultheis and Kjelvik (17) convincingly argue that students learn best the nature of science when confronted with "messy" authentic data that are both engaging and realistic. Our participants, however, still conceptualized graphing those data as a basic skill. Their view contrasts with established research (47, 48) that suggests that interpreting graphs is a difficult task for novice learners because of the large number of representation practices employed in graph construction (e.g., translating data from tables into averages which are then plotted). Graphing is not as much a skill as an epistemological practice (48). This apparent disconnect between participants' views that graphing is "basic" and research indicating the opposite suggests that larger-scale QR conceptualization surveys of biology faculty would be helpful in developing tools and resources that identify and ameliorate potential misunderstandings.

Faculty attributes and the variation in the meaning of QR

Conceptual sensemaking through data was the most recorded QR conceptualization and was especially emphasized by participants who self-described as ecologists/evolutionary biologists, whereas thinking in numbers was recorded somewhat less frequently by this group. This contrasted with participants who self-identified as cellular/molecular biologists who recorded both skills equally. While this may be a limitation of the small number of cellular/molecular biologists in our sample, this difference in emphasis in the two sophisticated skills may reflect the nature of the two disciplines, as was hypothesized by Clemmons et al. (10). Ecology has both strong empirical and strong theoretical mathematical roots (57). Beginning in the early 1960s, mathematical models were developed to investigate predator-prey dynamics, competitive interactions, and population dynamics (58). Graduate programs in ecology often require advanced training in mathematics and statistics. In contrast, traditional cellular and molecular biology initially focused on more qualitative aspects of DNA, proteins, and other cellular processes (59), although recent advances in technology have increasingly led to more quantitative data sets in bioinformatics and genomics (31).

Early- (0 to 4 yr) and late-career (20+) participants were most similar to each other in their conceptualizations of QR; all nine codes were recorded for each group, despite mostly early-career participants being familiar with *Vision and Change* (Table 1). We hypothesized that an awareness of *Vision and Change* might influence their conceptualization of QR and the need to include QR instruction in their teaching. Indeed, four of the five early-career participants were aware of the five core concepts and six core skills called for in the *Vision and Change* document, including the call to increase training in QR. The participants who had been teaching the longest, although not familiar with *Vision and Change*, indicated that they began incorporating QR into their introductory courses because they saw that students lacked this ability, often when they saw these students again in their upper-level courses. Perhaps later career participants arrived at the need for QR instruction in an organic, experiential way from their experiences in the classroom. It was also interesting to note that early- and late-career participants recorded both the sophisticated and basic QR skills, whereas the middle career participants did not record applying comparative/inferential statistics or using descriptive statistics. It would be interesting to investigate the role of technology in this difference. Perhaps midcareer participants found some QR skills less important as students learned to rely on technology (e.g., statistical software) but those skills became reemphasized for the early-career participants as part of their familiarity with *Vision and Change*.

Interestingly, there was no difference in sophisticated QR conceptualizations among institutions of different Carnegie classifications; for example, all institutional levels recorded conceptual sensemaking through data and thinking in numbers. There was more variation in the recording of basic QR skills, which might reflect the more diverse nature of student preparedness among differing institutional levels.

Recommendations/conclusions

Our study reveals two fruitful areas for further research. First, understanding better how biology faculty conceptualize QR can lead to targeted curriculum development, for example, addressing the skills identified in the nine codes. Our study suggests that faculty may put more emphasis on sophisticated skills and view some skills, e.g., creating/describing graphical data, as simpler than they actually are. This has potential implications, particularly at the introductory biology level, if faculty perceive students as more "ready" for QR than they actually are. Understanding that QR skills can be divided thematically into basic or sophisticated groupings can help faculty scaffold student development both within introductory courses and as students progress through their academic program. Hester et al. (11)

and Eliassen et al. (23) recommend putting mathematical skills into biological contexts early and focusing on a gradual buildup of quantitative skills throughout the curriculum. Introducing QR skills early in the curriculum, and starting with basic skills, could increase students' math self-concept (34) and encourage them to further develop more sophisticated QR skills. Experiences that positively shift students' attitudes about science and learning, and that promote self-efficacy, should be sought. Hoskins et al. (51) developed the C.R.E.A.T.E. methods to positively affects students' abilities to access primary literature; the method has a significant focus on interpreting data.

Second, our results echo the *Vision and Change Call to Action* to incorporate QR skills training at the undergraduate level, but they also point to the need to "close the loop" between biology educators and biology faculty who may not be aware of discipline-based education research. The lack of familiarity with *Vision and Change* among our participants likely reflects that of the biology faculty at large. *Vision and Change* and the BioCore (8) and BioSkills (10) guides are powerful tools for aligning curriculum with pedagogy and assessment, but widespread adoption is crucial. The Association of American Colleges and Universities (60) published a Quantitative Literacy VALUE rubric whose utility was to provide a basic framework of QR expectations that could be shared nationally. Moving forward, we advocate that biology departments begin internal dialog on curricular reform and assessment, pairing education-focused faculty with research-focused faculty to "spread the word." Fruitful next steps would be to expand these within-department dialogs to across-departments dialogs (e.g., chemistry, physics, mathematics, engineering) to exchange QR conceptualizations across STEM disciplines. This could help immeasurably in demonstrating to undergraduates the cross-disciplinary context of mathematics. Our study utilized an in-depth interview protocol with a small number of participants from a small number of institutions; expanding this work to survey-based research of more faculty and institutions, including the critical group of community colleges, which educate up to 40% of biology undergraduates (30), is warranted.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 0.3 MB.

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REFERENCES

1. National Research Council (US) Committee on Undergraduate Biology Education to Prepare Research Scientists for the 21st Century. 2003. BIO2010: transforming undergraduate education for future research biologists. National Academies Press, Washington, DC. https://doi.org/10.17226/10497.
2. Association of American Medical Colleges – Howard Hughes Medical Institute Joint Committee. 2009. Scientific foundations for future physicians. AAMC, Washington, DC.
3. American Association for the Advancement of Science. 2011. Vision and change in undergraduate biology education: a call to action. AAAS, Washington, DC.
4. Speth EB, Momsen JL, Moyerbrailean GA, Ebert-May D, Long TM, Wyse S, Linton D. 2010. 1, 2, 3, 4: Infusing quantitative literacy into introductory biology. CBE Life Sci Educ 9:323–332. https://doi.org/10.1187/cbe.10-03-0033.
5. Mayes R, Long T, Huffling L, Reedy A, Williamson B. 2020. Undergraduate quantitative biology impact on biology preservice teachers. Bull Math Biol 82:63. https://doi.org/10.1007/s11538-020-00740-z.
6. Strasser CA, Hampton SE. 2012. The fractured lab notebook: undergraduates and ecological data management training in the United States. Ecosphere 3:1–18. https://doi.org/10.1890/ES12-00139.1.
7. National Research Council (US) Committee on a New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution. 2009. A new biology for the 21st century: ensuring the United States leads the coming biology revolution. National Academies Press, Washington, DC.
8. Brownell SE, Freeman S, Wenderoth MP, Crowe AJ. 2014. BioCore Guide: a tool for interpreting the core concepts of Vision and Change for biology majors. CBE Life Sci Educ 13:200–211. https://doi.org/10.1187/cbe.13-12-0233.
9. Laungani R, Tanner C, Brooks TD, Clement B, Clouse M, Doyle E, Dworak S, Elder B, Marly K, Schofield B. 2018. Finding some good for an invasive species: introduction and assessment of a novel CURE to improve experimental design in undergraduate biology classrooms. J Microbiol Biol Educ 19:19.2.68. https://doi.org/10.1128/jmbe.v19i2.1517.
10. Clemmons AW, Timbrook J, Herron JC, Crowe AJ. 2020. BioSkills Guide: development and national validation of a tool for the interpreting the *Vision and Change* core competencies. LSE 19:ar53. https://doi.org/10.1187/cbe.19-11-0259.
11. Hester S, Buxner S, Elfring S, Nagy L. 2014. Integrating quantitative thinking into an introductory biology course improves students' mathematical reasoning in biological contexts. CBE Life Sci Educ 13:54–64. https://doi.org/10.1187/cbe.13-07-0129.
12. Freeman S, Haak D, Wenderoth MP. 2011. Increased course

structure improves performance in introductory biology. CBE Life Sci Educ 10:175–186. https://doi.org/10.1187/cbe.10-08-0105.

13. Sax LJ, Kanny MA, Riggers-Piehl TA, Whang H, Paulson LN. 2015. "But I'm not good at math": the changing salience of mathematical self-concept in shaping women's and men's STEM aspirations. Res High Educ 56:813–842. https://doi.org/10.1007/s11162-015-9375-x.
14. Hachtmann F. 2012. The process of general education reform from a faculty perspective: a grounded theory approach. J Gen Educ 61:16–38. https://doi.org/10.1353/jge.2012.0007.
15. Kelly GJ. 2008. Inquiry, activity, and epistemic practice, p 99–117. *In* Duschl RA, Grandy RE (ed), Teaching scientific inquiry: recommendations for research and implementation. Sense Publishing, The Netherlands.
16. Nersessian N. 2008. Inquiry: how science works, p 57–79. In Duschl RA, Grandy RE (ed), Teaching scientific inquiry: recommendations for research and implementation. Sense Publishing, The Netherlands.
17. Schultheis EH, Kjelvik MK. 2015. Data nuggets: bringing real data into the classroom to unearth students' quantitative and inquiry skills. Am Biol Teach 77:19–29. https://doi.org/10.1525/abt.2015.77.1.4.
18. Jiménez-Aleixandre MP, Crujeiras B. 2017. Epistemic practices and scientific practices in science education, p 69–80. *In* Taber KS, Akpan B. (eds) Science education: an international course companion. SensePublishers, Rotterdam.
19. Sadler TD, McKinney L. 2010. Scientific research for undergraduate students: a review of the literature. J Coll Sci Teach 39:43–49.
20. Hanauer DI, Graham MJ, Hatfull GF. 2016. A measure of college student persistence in the sciences (PITS). LSE 15:ar54. https://doi.org/10.1187/cbe.15-09-0185.
21. Hanauer DI, Dolan EL. 2014. The project ownership survey: measuring differences in scientific inquiry experience. CBE Life Sci Educ 13:149–158. https://doi.org/10.1187/cbe.13-06-0123.
22. Hart Research Associates. 2015. Falling short? College learning and career success. Hart Research Associates, Washington, DC.
23. Eliassen S, Kolding J, Smedmark J, Vandvik V. 30 to 31 March 2017. Numerical competence and quantitative skills for BSc-students in biology. Presented at the MNT conference, Oslo. University of Bergen, Norway.
24. Feser J, Vasaly H, Herrera J. 2013. On the edge of mathematics and biology integration: improving quantitative skills in undergraduate biology education. CBE Life Sci Educ 12:124–128. https://doi.org/10.1187/cbe.13-03-0057.
25. Andrews SA, Aikens ML. 2018. Life science majors' math-biology task values relate to student characteristics and predict the likelihood of taking quantitative biology courses. J Microbiol Biol Educ 19:jmbe-19-80. https://doi.org/10.1128/jmbe.v19i2.1589.
26. Wachsmuth LP, Runyon CR, Drake JM, Dolan EL. 2017. Do biology students really hate math? Empirical insights into undergraduate life science majors' emotions about mathematics. LSE 16:ar49. https://doi.org/10.1187/cbe.16-08-0248.
27. Matthews KE, Hodgson Y, Varsavsky C. 2013. Factors influencing students' perceptions of their quantitative skills. Int J Math Educ Sci Tech 44:782–795. https://doi.org/10.1080/0020739X.2013.814814.
28. Beck CW. 2018. Infusion of quantitative and statistical concepts into biology courses does not improve quantitative literacy. J Coll Sci Teach 47:62–71.
29. Leonelli S. 2014. What difference does quantity make? On the epistemology of Big Data in biology. Big Data Soc 1. https://doi.org/10.1177/2053951714534395.
30. Corwin LA, Kiser S, LoRe SM, Miller JM, Aikens ML. 2019. Community college instructors' perceptions of constraints and affordances related to teaching quantitative biology skills and concepts. CBE Life Sci Educ 18:ar64. https://doi.org/10.1187/cbe.19-01-0003.
31. Mathur V, Arora GS, McWilliams M, Russell J, Rosenwald AG. 2019. The Genome Solver Project: faculty training and student performance gains in bioinformations. J Microbiol Biol Educ 20:20.1.4. https://doi.org/10.1128/jmbe.v20i1.1607.
32. Marsteller P. 2010. Beyond BIO2010: integrating biology and mathematics: collaborations, challenges, and opportunities. CBE Life Sci Educ 9:141–142. https://doi.org/10.1187/cbe.10-06-0084.
33. Massimelli J, Denaro K, Sato B, Kadandale P, Boury N. 2019. Just figures: a method to introduce students to data analysis one figure at a time. J Microbiol Biol Educ 20:20. https://doi.org/10.1128/jmbe.v20i2.1690.
34. Cooper KM, Krieg A, Brownell SE. 2018. Who perceives they are smarter? Exploring the influence of student characteristics on student academic self-concept in physiology. Adv Physiol Educ 42:200–208. https://doi.org/10.1152/advan.00085.2017.
35. Shulman LS. 1986. Those who understand: knowledge growth in teaching. Educ Res 15:4–14. https://doi.org/10.3102/0013189X015002004.
36. Manduca CA, Iverson ER, Luxenberg M, Macdonald RH, McConnell DA, Mogk DW, Tewksbury BJ. 2017. Improving undergraduate STEM education: the efficacy of discipline-based professional development. Sci Adv 3:e1600193. https://doi.org/10.1126/sciadv.1600193.
37. Polkinghorne DE. 1989. Phenomenological research methods. Springer, Boston, MA.
38. Patton MQ. 2002. Qualitative research and evaluation methods (3rd ed). Sage Publishing, Thousand Oaks, CA.
39. Rubin HJ, Rubin IS. 2012. Qualitative interviewing: the art of hearing data. Sage Publishing, Thousand Oaks, CA.
40. Aikens ML, Dolan EL. 2014. Teaching quantitative biology: goals, assessments, and resources. Mol Biol Cell 25:3478–3481. https://doi.org/10.1091/mbc.E14-06-1045.
41. Mayes RL, Forrester J, Christus JS, Peterson F, Walker R. 2014. Quantitative reasoning learning progressions: the matrix. Numeracy 7:5. https://doi.org/10.5038/1936-4660.7.2.5.
42. Stanhope L, Ziegler L, Haque T, Le L, Vinces M, Davis GK, Zieffler A, Brodfuehrer P, Preest M, M Belitsky J, Umbanhowar C, Overvoorde PJ. 2017. Development of a biological science quantitative reasoning exam (BioSQuaRE). LSE 16:ar66. https://doi.org/10.1187/cbe.16-10-0301.
43. Moustakas C. 1994. Phenomenological research methods. Sage Publishing, Thousand Oaks, CA.
44. Syed M, Nelson SC. 2015. Guidelines for establishing reliability

when coding narrative data. Emer Adulthood 3:375–387. https://doi.org/10.1177/2167696815587648.

45. Lombard M, Snyder-Duch J, Bracken CC. 2002. Content analysis in mass communication: assessment and reporting of intercoder reliability. Human Comm Res 28:587–604. https://doi.org/10.1111/j.1468-2958.2002.tb00826.x.
46. Saldaña J. 2015. The coding manual for qualitative researchers. Sage Publishing, Thousand Oaks, CA.
47. Bowen GM, Roth W-M. 1998. Lecturing graphing: what features of lectures contribute to student difficulties in learning to interpret graphs? Res Sci Educ 28:77–90. https://doi.org/10.1007/BF02461643.
48. Bowen GM, Roth W-M, McGinn MK. 1999. Interpretations of graphs by university biology students and practicing scientists: toward a social practice view of scientific representation practices. J Res Sci Teach 36:1020–1043. https://doi.org/10.1002/(SICI)1098-2736(199911)36:9<1020::AID-TEA4>3.0.CO;2-#.
49. Schultheis EH, Kjelvik MK. 2020. Using messy, authentic data to promote data literacy and reveal the nature of science. Am Biol Teach 82:439–446. https://doi.org/10.1525/abt.2020.82.7.439.
50. Thompson PW. 2011. Quantitative reasoning and mathematical modeling, p 33–57. In Hatfield LL, Chamberlain S, Belbase S (ed), New perspectives and directions for collaborative research in mathematics education: WISDOMe Monograph Vol. 1. University of Wyoming, Laramie, WY.
51. 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.
52. diSessa AA. 2004. Metarepresentation: native competence and targets for instruction. Cogn Instr 22:293–331. https://doi.org/10.1207/s1532690xci2203_2.
53. Roth W-R, McGinn MK. 1997. Graphing: cognitive ability or practice? Sci Ed 81:91–106. https://doi.org/10.1002/(SICI)1098-237X(199701)81:1<91::AID-SCE5>3.0.CO;2-X.
54. Nathan MJ, Koedinger KR, Alibali MW. 2001. Expert blind spot: when content knowledge eclipses pedagogical content knowledge. Proceedings of the third international conference on cognitive science. UTHM, Malaysia.
55. Shah P, Freedman EG. 2011. Bar and line graph comprehension: an interaction of top-down and bottom-up processes. Top Cogn Sci 3:560–578. https://doi.org/10.1111/j.1756-8765.2009.01066.x.
56. Harsh JA, Schmitt-Harsh M. 2016. Instructional strategies to develop graphing skills in the college science classroom. Amer Biol Teach 78:49–56. https://doi.org/10.1525/abt.2016.78.1.49.
57. Łomnicki A, Lomnicki A. 1988. The place of modelling in ecology. Oikos 52:139–142. https://doi.org/10.2307/3565240.
58. Godfray HCJ, McLean AR. 2020. Lord Robert May (1936–2020). Science 368:1189. https://doi.org/10.1126/science.abc7800.
59. Short B. 2009. Cell biologists expand their networks. J Cell Biol 186:305–311. https://doi.org/10.1083/jcb.200907093.
60. Association of American Colleges and Universities. 2009. Quantitative literacy VALUE rubric. https://www.aacu.org/value/rubrics/quantitativeliteracy.