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Online, Interactive Modules Improve Quantitative Skills in Community College Biology Students

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Abstract

Introductory courses in biology often lack sufficient emphasis on quantitative skills and interdisciplinary problem solving, leaving many students unprepared for more advanced biology coursework and hampering their ability to pursue biology research careers. MathBench Biology Modules were created to enhance the quantitative skills of biology students by leveraging the unique advantages of the online environment (e.g., self-pacing, opportunities for practice, and immediate, individualized feedback). Using a pre-/post-design, we tested the ability of MathBench modules to improve student quantitative skills and their attitudes towards the integration of math and biology in a community college introductory biology course, where instructors face multiple challenges to integrating quantitative content. Ten sections of the course incorporated MathBench into laboratory and lecture content (MathBench group, $N = 124$ students), while five sections covered the same laboratory and lecture content without MathBench (comparison group, $N = 31$ students). On average, students who used MathBench experienced gains in their quantitative skills, while those in the comparison group did not. For students with the lowest level of preparation in math, using MathBench was associated with improvements in quantitative skill only if they were concurrently enrolled in a math class. Neither group of students demonstrated changes over the semester in their attitudes towards the integration of math and biology. Qualitative data indicated that MathBench group students could identify multiple aspects of how MathBench contributed to their learning, including providing new content, alternative approaches to learning, and additional opportunities to practice new skills. Our work demonstrates how learner-centered technologies can be used effectively to supplement traditional instruction in the community college context.

Keywords Online modules · Biology · Mathematics · Quantitative skills · Community college · Digital resources

Introduction

Graduates in STEM (Science, Technology, Engineering, and Mathematics) fields are often perceived by employers as inadequately prepared for the workplace, particularly with respect to twenty-first century skills such as quantitative reasoning and problem solving (Hart Research Associates, 2015). This is especially pronounced in the biological sciences, which has a long tradition (and an enduring perception among students) of emphasizing descriptive and qualitative approaches over quantitative approaches (Gross, 2000; Wachsmuth et al., 2017). Biology research and industry have a growing reliance on quantitative data and reasoning (Feser et al., 2013), which has increased the urgency for universities to equip the next generation of biologists with these critical skills (Gross, 2000; National Research Council, 2003, 2009). In 2011, the American Association for the Advancement of Science (AAAS) published *Vision and Change in Undergraduate Biology Education: A Call to Action*, which created a roadmap for revising undergraduate education in the biological sciences. The report included recommendations for both "what to teach" and "how to teach" biology. Regarding "what to teach," the most prevalent recommendation was to promote conceptual understanding and emphasize overarching principles instead of rote memorization. Regarding the "how to teach," the report highlighted the need to promote

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six core competencies, each of which is arguably dependent on well-developed quantitative skills. These are (1) the ability to apply the process of science, (2) the ability to use quantitative reasoning, (3) the ability to use modeling and simulation, (4) the ability to tap into the interdisciplinary nature of science, (5) the ability to communicate and collaborate with other disciplines, and (6) the ability to understand the relationship between science and society.

In the wake of *Vision and Change* (AAAS, 2011), numerous approaches have been suggested for strengthening quantitative skills in biology students, many of which are summarized in the AAAS (2015) follow-up report *Vision and Change: Chronicling Change, Inspiring the Future.* Despite their growing prevalence, these approaches are still not the norm (Feser et al., 2013; Indorf et al., 2021), resulting in students who are ill-prepared for the requirements of upper-level biology courses and postgraduate biology careers. There is an emerging consensus that quantitative fluency in biology students cannot be achieved by developing mathematical skills and biological content knowledge in isolation and then expecting students to easily apply their mathematical knowledge to new biological contexts. Rather, quantitative approaches must be deeply embedded throughout all levels of the biology curriculum (Gross, 2004).

Our solution to this challenge was to create an online resource, MathBench Biology Modules, that can be used to supplement existing course content. The modules are well-aligned with *Vision and Change* (AAAS, 2011) and promote skills such as problem solving, quantitative reasoning, and application to real situations. MathBench modules are self-contained, adaptive to students' background knowledge, and can be assigned as homework for students to complete outside of class. The guiding philosophy of MathBench is learner-centered: Students work their way through the module content at their own pace and can decide how much effort they want to invest. Furthermore, the modules are designed to engage students and ease math anxiety through storytelling, playful interactive simulations, and practice problems that provide targeted feedback to guide students towards solutions (Nelson et al., 2009). The modules are intended to be integrated into biology courses at all levels of the curriculum, so that students experience authentic quantitative approaches early on and have this knowledge repeatedly reinforced as they move through their degree programs. MathBench has been shown to increase quantitative skills of students enrolled in introductory (Thompson et al., 2010) and second-year (Thompson et al., 2013) biology courses at a large, public 4-year university and in an upper-level biology course at a second large, public 4-year university (Karsai et al., 2015).

We describe here a study designed to measure the impact of interactive, online modules on the quantitative skills of introductory biology students at a large, public community college. Community colleges in the USA educate up to 40% of biology undergraduates yet are severely underrepresented in the biology education literature (Corwin et al., 2019), so it is unclear whether the teaching strategies that are successful at 4-year institutions are similarly successful at 2-year institutions. Quantitative skills have been shown to correlate strongly with academic success in biological sciences and related fields (Flanagan & Einarson, 2017; Llamas et al., 2012; Matthews et al., 2013; Sadler & Tai, 2007; Wolff et al., 2014), as well as confidence in their career readiness (Matthews et al., 2013). Therefore, it is critically important that community college students develop these important skills so that when they transfer to 4-year institutions to complete their biology degrees, they are on equal footing with their peers and similarly well-prepared for their future careers.

Theoretical Background

Challenges to Integrating Math and Biology in 4-Year and 2-Year College Settings

Integrating quantitative approaches into the biology curriculum has proven difficult for many reasons. Some biology faculty received their professional training during a time when quantitative skills were not emphasized and consequently have difficulty envisioning how and where to incorporate more quantitative approaches into their teaching. Others may be adept with the application of quantitative skills to their research but may lack the pedagogical content knowledge or self-efficacy to teach these skills effectively (Indorf et al., 2021). Opportunity to engage in professional development to learn innovative, effective ways of teaching interdisciplinary content is limited for most faculty and especially so for community college faculty (Holmberg et al., 2021). Incorporating new content and approaches inevitably requires that some existing content be sacrificed, which means that instructors must reprioritize the content that they include (Gross, 2004). Finally, revamping course content requires time that is often sorely limited, and these efforts are rarely recognized in the formal faculty reward structure (Marsteller et al., 2010).

The challenges of incorporating quantitative material into biology courses have been recognized globally and are compounded by heterogeneity of student preparation in math, especially in introductory biology courses that serve mixed audiences of biology majors, students majoring in related fields, and those taking the course to fulfill general education science requirements. Some students struggle with quantitative material because they have weak preparation in mathematics (Scott, 2016; Tariq, 2005), while others have sophisticated backgrounds in mathematics, yet are unable to transfer their mathematical knowledge to biological contexts (Hester et al., 2014).

Many instructors perceive that a sizable fraction of biology students are math-averse or have low self-efficacy with respect to applying math to biological contexts (Andrews & Aikens, 2018; Flanagan & Einarson, 2017; Koenig, 2011; LeBard et al., 2014; Thompson et al., 2013; Williams et al., 2021). They may be hesitant to devote biology class time to teaching mathematical concepts that some of the students have already mastered and that others will resist learning. The resulting lack of quantitative emphasis in introductory biology courses does little to change the impression of many students that biology is a non-quantitative field, which further hampers their investment in learning the quantitative skills necessary for success in subsequent coursework, research experiences, and careers.

The community college setting provides additional challenges to strengthening the quantitative emphasis of the biology curriculum. Open access policies result in more pronounced heterogeneity in quantitative skills than is observed in 4-year settings (e.g., 59% of community college students need developmental math, compared to 33% at 4-year institutions (Chen, 2016)). The prevalence of math anxiety is also likely to be higher due to many students' weak math preparation (Andrews & Aikens, 2018; Pajares & Miller, 1994) and the greater numbers of nontraditional students, who may not have taken a math course in a long time (Betz, 1978; Jameson & Fusco, 2014).

Despite the substantial attention to developing students' quantitative skills in 4-year settings, comparatively little work has been done to understand the particular needs of students and instructors at community colleges. Corwin et al. (2019) interviewed community college instructors to better understand their needs with respect to incorporating quantitative reasoning into their biology courses. Their concerns mirrored those of 4-year instructors with important distinctions. They recognized the widely varying levels of math preparation and math efficacy, which resulted in them needing to devote more time to assisting individual students when quantitative concepts and skills were covered. They also felt they lacked the flexibility to modify the content of their courses because of transfer articulation requirements and the need for consistency among multiple sections of the same course. Lack of time to revise curricula was also a major barrier due to heavy teaching loads and compensation models that recognize contact hours but not course development time. Both lack of mathematical knowledge and lack of knowledge about how to effectively teach quantitative subjects were identified as barriers. Despite these substantial challenges, the community college instructors expressed a desire for more curricular resources that could be used to strengthen the quantitative emphasis of their courses.

The Role of Affect in Learning Quantitative Subjects

A student's investment in learning a particular subject and their persistence in related fields of study are strongly influenced by their attitudes towards the subject (Wachsmuth et al., 2017). This has been conceptualized by Eccles et al. (1983) using expectancy-value theory, which explains educational achievement as being the product of a student's confidence in their ability to succeed in a particular educational task and how important, useful, or enjoyable they perceive the task to be. In the context of learning math and applying it to biology, this means that student learning is affected by their intrinsic enjoyment of math, their perception of the relevance of math to the field of biology, and their perception of the difficulty of using math to deepen their understanding of biology. Students who enjoy math and think it is important to the field of biology are more motivated to learn quantitative aspects of biology. Consequently, they may be more likely to succeed in their biology coursework and persist in biology career paths. Conversely, those who dislike math, fail to see its relevance to biology, or perceive it as difficult may be more likely to avoid quantitative aspects of biology and perhaps even choose career paths that do not emphasize quantitative approaches.

The topic of learning math is particularly fraught with preconceptions and negative associations, many of which have their roots in early childhood educational experiences (Ashcraft & Krause, 2007; Flanagan & Einarson, 2017). From an early age, students may embrace a fixed mindset and self-identify as "not a math person," which has negative repercussions for subsequent academic success. The term "math anxiety" is used to refer to a general negative affect associated with mathematics (Betz, 1978). It can be manifested as feelings of dread, apprehension, and even the perception of physical pain (Lyons & Beilock, 2012).

Math anxiety interferes with working memory, resulting in impaired learning and impaired performance on quantitative tasks (Ashcraft & Krause, 2007). Indeed, this close relationship makes it difficult to discern whether poor achievement on quantitative assessments is due to deficiencies in knowledge or difficulty demonstrating knowledge due to math anxiety. Many of the difficulties that college students have applying math to biological contexts have been ascribed to math anxiety (Quinnell et al., 2012). Math anxiety leads to a negative spiral– students who feel anxious about math avoid it, further weakening their quantitative skills relative to those who enjoy math, making it ever less likely that they will enroll in degree programs that require quantitative coursework and subsequently enter careers that rely on quantitative approaches.

Online Modules as a Strategy for Integrating Math and Biology

Online modules are particularly appropriate for strengthening the links between math and biology and hold great promise for easing math anxiety. They can be dynamic and visually engaging (Hoy, 2004; Yang et al., 2021) and are superior to didactic instruction for many topics, especially those that involve complex biological processes (e.g., meiosis: Goff et al., 2017; cellular respiration: Goff et al., 2018). The use of modules developed by those with quantitative expertise allows students to develop more sophisticated understanding even when their instructor's knowledge of quantitative approaches is limited. They provide a great deal of learner control, allowing students to adjust the time and effort they devote to what they need to feel comfortable with the content (Chen et al., 2018; Nelson et al., 2009). Online modules can be constructed to conform to evidence-based design principles to enhance learning, such as spaced practice (Clark & Mayer, 2008) and ensuring that learning elements of differing modalities are located close together in space and time (Brasier et al., 2019). Online modules completed outside of class time can also prepare students for more engaged learning in the classroom (e.g., flipped classes) (Goff et al., 2018).

MathBench (Nelson et al., 2009) uses simple, clear, and intuitive explanations of the math involved to help students bridge the gap between biology and mathematical formalism. We deliberately employ uncomplicated colloquial speech, since the use of a "personal voice" (i.e., writing directly to the student rather than in the third person) helps students learn material more deeply and with less anxiety (Moreno & Mayer, 2000). MathBench goes beyond drill-type online activities to offer targeted adaptive feedback to isolate student errors in judgment. Students are frequently prompted for solutions to problems. They receive immediate acknowledgement if their answers are correct. If their answers are incorrect, they receive immediate feedback that nudges them towards the correct answer or refers them to other sections of the module to review the necessary concepts before trying again. This feedback is tailored to the most common types of student errors, and students making repeated errors are given increasingly detailed suggestions for how to solve the problem at hand.

MathBench attempts to strike a balance between demonstrating how to solve problems and allowing students to practice finding the solutions themselves. Rather than allowing students to simply flip through the screen of a worked problem, or passively watch a simulation (Tversky et al., 2002), the modules encourage them to actively construct knowledge by making and testing predictions (Reed, 1985; Wender & Muehlboeck, 2003) and by "self-explaining" steps in a problem or process (Atkinson et al., 2005). To help students transfer their quantitative knowledge to novel contexts, our modules are built around storylines that contextualize the mathematical information being learned and then explicitly teach the skills needed to "distill" mathematics from those real-world situations. Our storylines are similar to case-based studies, which are generally regarded as valuable instructional techniques for building thinking skills for complex tasks (Mayer, 2008).

Research Questions

We explored the impact of online modules on community college student quantitative skills and attitudes by focusing on three research questions:

1. Do students' quantitative skills improve after using MathBench?
2. Do students' enjoyment of mathematics and perception of the importance of mathematics to biology change after using MathBench?
3. In what ways do students feel MathBench impacted their learning?

Methods

Context of the Study

The study was conducted at an open access, public community college in the Mid-Atlantic region that enrolls > 50,000 students in > 100 associate degree and certificate programs. MathBench modules were integrated into the curriculum of BIOL 107 (Principles of Biology). This course is the first in a two-course sequence that is intended for natural science majors. It provides an introduction to the molecular and cellular basis of life, including enzymes, photosynthesis, cellular respiration, genetics, reproduction, and development. The course was organized into approximately 40 sections of up to 24 students, who met three times per week for 50-min lecture sessions and once per week for a 3-h laboratory session. For the purposes of this study, ten sections (taught by five instructors) incorporated MathBench into their curriculum (designated as the MathBench group). Five sections (taught by three instructors) that did not use MathBench served as the comparison group.

In the MathBench sections, six modules were assigned. Four were selected to bolster student understanding of laboratory material, and two were intended to supplement lecture content (Table 1). Students were expected to complete the assigned modules outside of class time during the week leading up to the relevant laboratory or lecture. After working through the modules, students were assessed on the module content with a brief, 5–10 question multiple-choice quiz that was delivered online through the course

Table 1 MathBench modules used in BIOL 107 Principles of Biology and the specific quantitative skills and concepts emphasized in each module

Modules	The size of things	Tricks with division	Normal distributions and the scientific method	Chopping up plasmids	Basic rules of probability	Intro to Punnett squares
MathBench quantitative concepts and skills emphasized						
Functions						
Graphs			✓			
Magnitude	✓	✓				
Model structure/iteration			✓			✓
Probability			✓		✓	✓
Rates and equilibria						
Statistics			✓			✓
Unit conversions	✓					
Distill biology into math	✓	✓	✓	✓	✓	✓
Integration with BIOL 107 principles of biology course content						
Lab 1: Microscopy	A	A				
Lab 2: Diffusion and osmosis			A			
Lab 3: Organic molecules			a			
Lab 4: Enzymes			a			
Lab 5: Cell respiration			a			
Lab 6: Photosynthesis			a			
Lab 7: Mitotic cell division	a	a				
Lab 8: Plant tissues	a	a				
Lab 9: Animal tissues	a	a				
Lab 10–12: DNA				A		
Lecture: Genetics					A	A

All modules are designed to contribute to a student's overall ability to use mathematics to describe and understand biological phenomena (i.e., distill biology into math). Upper- and lowercase letters denote when MathBench modules were first assigned (A) as homework during the week leading up to a specific lab and when previously assigned MathBench module were applicable (a) to subsequent labs

learning management system. The quizzes served primarily as an incentive for students to complete the modules carefully and on time.

Data Collection and Research Instruments

Students in both the MathBench and comparison groups were administered a two-part survey using a pre-/post-design. The pre-survey was given at the beginning of the semester, prior to using MathBench modules, and the post-survey was given at the end of the semester, after the completion of the last MathBench module. Surveys were administered during class time in hard copy, with students entering their responses on a Scantron sheet for automated analysis. Students earned a very small number points (amounting to ~ 1% of the course total) towards their final grade for completing the surveys, irrespective of the number of questions they answered correctly.

Both surveys consisted of an 18-item, multiple-choice quantitative skills test that was designed to be a generalized assessment of eight quantitative topic areas considered to be important for biologists and reinforced repeatedly throughout the suite of > 40 MathBench modules (Thompson et al., 2010). Each MathBench module touches on one or more of these topic areas. Generally, a given course would not cover all of the topic areas, so a student's exposure to them would vary from course to course, depending on which modules were incorporated into the course's curriculum. Each topic area was represented on the assessment by one or more questions of varying difficulty. The total score on the quantitative skills test was designed to be a global measure of the student's ability to use mathematics to describe and understand biological phenomena. Cronbach's alpha for the quantitative skills pre-test was 0.72, indicating an acceptable level of internal consistency.

The individual items were nearly identical between the pre- and post-tests, with only minor contextual or numerical changes. Each item had four possible answers from which students could choose, or they could select the option "I don't know how to approach this question." Previous research on introductory biology students at a 4-year university showed that scores were correlated with previous math background, with average pre-test scores ranging from 6 out of 18 questions correct for students who had completed algebra to about 10 out of 18 questions correct for students who had completed at least two semesters of calculus (Thompson et al., 2010).

In addition to the quantitative skills items, we included items that asked students about their attitudes towards math (*It is important for biologists to know math*, and *I like math*), which were rated on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree). On the post-survey only, we asked students to indicate the highest level of math they had previously completed (algebra, precalculus, calculus 1, calculus 2), whether they were concurrently enrolled in a math class, whether they felt they had improved their scientific content knowledge or quantitative skills over the semester, and what course components contributed to this improvement. Finally, the post-survey for the MathBench group asked two open-ended questions about the role of MathBench in the development of their scientific content knowledge and quantitative skills and their suggestions for further improvements to MathBench. The complete surveys are provided as Appendix 1 and Appendix 2.

We matched all substantially complete pre- and post-surveys, resulting in a sample of 124 MathBench group students and 33 comparison group students. The final sample represented only about half of the students initially enrolled in the course because some students opted not to complete one or both surveys and other students formally withdrew from the course prior to the post-survey being administered. Two of the comparison group students were omitted from analysis because they indicated in their survey responses that they had used MathBench, even though it had not been assigned to them, leaving 31 students in the comparison group.

Analysis of Quantitative Data

Changes in quantitative skill and attitudes over the course of the semester were analyzed with repeated measure analysis of variance. Pre- and post-survey values were the dependent variables. Group (MathBench, comparison) was entered in the model as a main effect. Based on previous research, we also included as main effects the highest math course completed (algebra, precalculus, calculus 1, calculus 2) and whether the student was concurrently enrolled in a math class (yes, no). We also conducted separate analyses of variance to see whether there were overall differences in pre- and post-test scores between the MathBench and comparison groups.

To investigate the impact of concurrent enrollment in a math class on the extent to which quantitative skills increased, we subdivided the MathBench group into two groups based on whether they began the semester having completed only algebra ($N=54$) or had completed at least one course beyond algebra ($N=69$). We then used analysis of variance to examine the interaction between math preparation and concurrent enrollment in math.

Analysis of variance was also used to compare student perceptions of learning gains across the semester and to investigate whether student perceptions correlated to the actual gains measured by the quantitative skills test. For all analyses, descriptive statistics are presented as adjusted means and standard errors, which take into account the influence of covariates.

Analysis of Qualitative Data

Responses to the open-ended survey question, “What role did MathBench Biology Modules have in the development of your scientific content knowledge and quantitative skills?”, were coded independently for themes by two biology education researchers. Student responses were coded into one or more themes, based on their content and complexity. From the start, there was a high agreement between the coders; however, disagreements were negotiated between the coders until they reached 100% agreement (Saldaña, 2015). Individual quotes from the open-ended survey questions were also used to support and contextualize findings that emerged from the quantitative analysis.

Results

Our findings are organized by research question:

1. *Do Students’ Quantitative Skills Improve After Using MathBench*?

   The MathBench group showed a significant improvement in quantitative skill test scores across the semester, while the comparison group showed no improvement (time*group interaction: $F_{1,142}=5.4389$, $p=0.0211$, Fig. 1). Students who were concurrently enrolled in a math course along with the Introductory Biology course showed greater improvements than those who were not concurrently enrolled in math (time*concurrent enrollment interaction: $F_{1,142}=8.1788$, $p=0.0049$). As has been found in previous studies, scores on the pre- and post-tests of quantitative skill were significantly correlated with a student’s previous math preparation (main effect of highest math completed: $F_{2,142}=4.916$, $p=0.0026$).

   Subsequent analyses of variance showed that there were no significant differences between the MathBench and comparison groups in the pre-test; however,

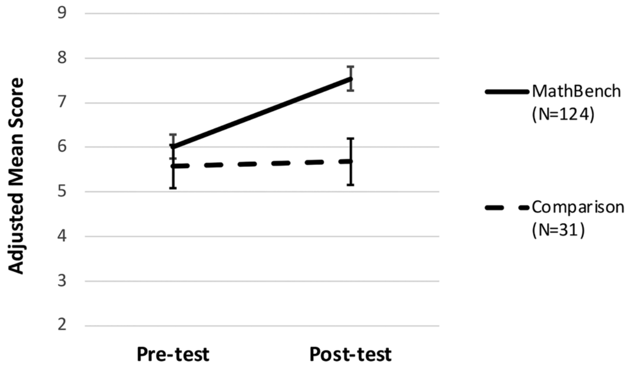


Fig. 1 Student scores on an 18-item quantitative skills test administered at the beginning and end of an Introductory Biology course. Students in the MathBench group ($N = 124$) completed MathBench modules as part of their assigned coursework, while those in the comparison group ($N = 31$) did not. Scores shown are adjusted means (with a maximum possible score of 18) and standard errors derived from repeated measures analysis of variance

there were significant differences overall between the MathBench and comparison groups in the post-test ($F_{1,153} = 9.4079$, $p = 0.0026$). Visual inspection of the proportion of correct answers for each question shows that the MathBench group outscored the comparison group for most questions (Fig. 2), especially the less difficult ones (i.e., the ones with a higher proportion of students answering correctly). Fewer differences between groups were apparent for the more difficult questions (i.e., the ones for which a low proportion of students answered correctly, often below that expected by chance).

To further investigate the relationship between a student's previous math preparation, concurrent enrollment in a math class, and the benefits of MathBench, we divided MathBench group students into two subgroups based on whether they began the semester having completed only algebra ($N = 54$) or had completed at least one course beyond algebra ($N = 69$). There was a significant interaction effect between previous math preparation and concurrent enrollment in math (overall: $F_{3,116} = 3.7090$, $p = 0.0136$, concurrent math*previous math interaction: $F_{1,116} = 8.799$, $p = 0.0038$). Students who had previously completed algebra and were concurrently enrolled in a math class showed the greatest gains, while those of similar math background who were not enrolled in a math class on average showed no improvement (Fig. 3). For students with higher levels of math background, concurrent enrollment in math did not have a large or consistently positive effect. MathBench alone was insufficient to produce gains in quantitative skill for students at the lowest levels of math proficiency.

2. *Do Students' Enjoyment of Mathematics and Perception of the Importance of Mathematics to Biology Change After Using MathBench?*

We gauged students' perception of the importance of math to biology and their enjoyment of math in both the pre- and post-survey. We asked students to rate the statements, "It is important for biologists to know math,"

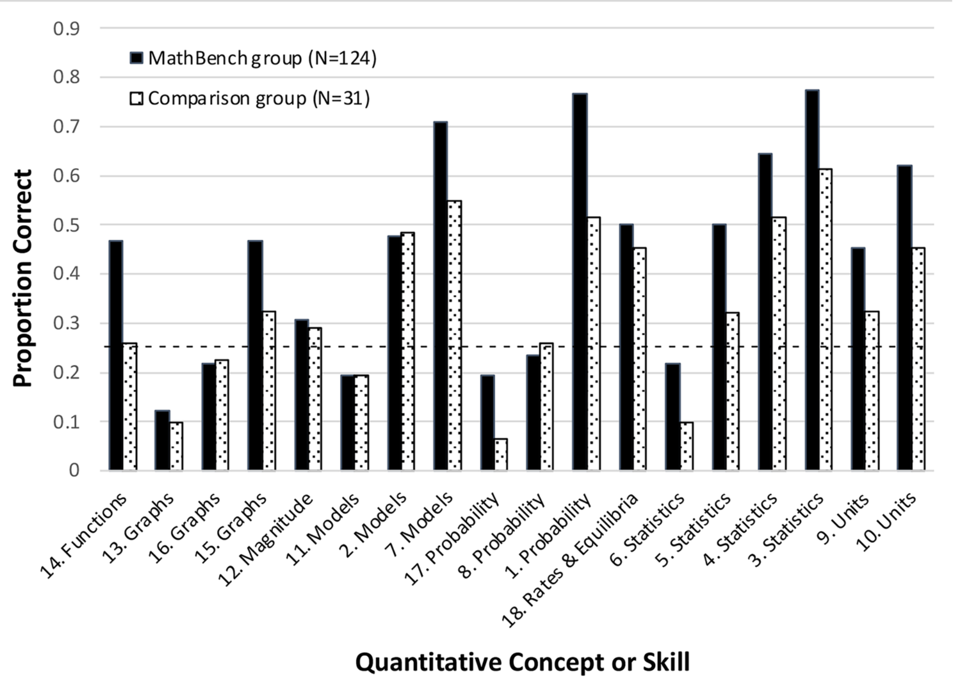


Fig. 2 Proportion of students in the MathBench ($N = 124$) and comparison ($N = 31$) groups who correctly answered each of the items on the quantitative skill post-test. Labels refer to the item numbers in Appendix 2. Items are grouped by topic and then sorted by difficulty (proportion of students who answered correctly). The proportion expected solely by chance (0.25) is shown by the dashed line

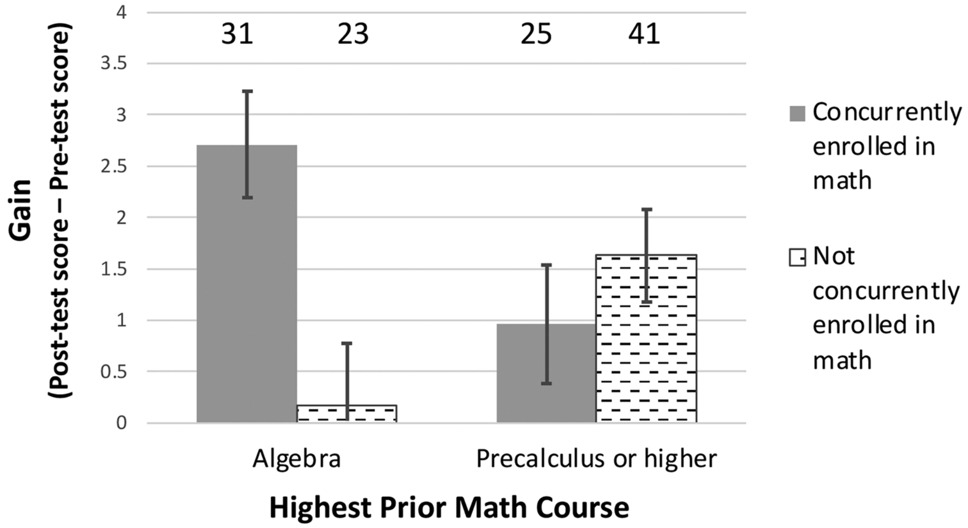


Fig. 3 Gain in quantitative skill (post-test score minus pre-test score) for students with differing levels of math preparation who were either concurrently enrolled in a math course while using MathBench in their Introductory Biology course, or who were not concurrently enrolled in a math course. Sample sizes are shown above the bars. There was a significant interaction between level of math preparation and concurrent enrollment in math ($F_{1,116}=8.799$, $p=0.0038$)

and "I like math" on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree).

On average, students agreed that biologists should know math. Adjusted mean scores fell between "agree" and "strongly agree" for this question on both the pre-survey (adjusted means and standard errors, MathBench group: 4.56 ± 0.08; comparison group: 4.49 ± 0.14) and the post-survey (adjusted means and standard errors, MathBench group: 4.48 ± 0.08; comparison group: 4.56 ± 0.13). There were no significant differences between groups in their level of agreement with this statement (main effect of group: $F_{1,138}=0.0001$, $p=0.9933$), and their level of agreement did not change over the semester (main effect of time: $F_{1,138}=0.0013$, $p=0.9708$; time*group interaction: $F_{1,138}=0.9181$, $p=0.3396$).

Student attitudes towards math were more neutral. Adjusted mean scores were at or slightly above "neither agree nor disagree" for both the pre-survey (adjusted means and standard errors, MathBench group: 3.31 ± 0.16; comparison group: 3.21 ± 0.27) and the post-survey (adjusted means and standard errors, MathBench group: 3.26 ± 0.17; comparison group: 2.99 ± 0.30). As with their attitudes about the importance of math, there were no significant differences between groups (main effect of group: $F_{1,138}=0.6482$, $p=0.4222$) in the extent to which they liked math and no significant changes over the semester (main effect of time: $F_{1,138}=0.6258$, $p=0.4303$; time*group interaction: $F_{1,138}=0.5525$, $p=0.4586$).

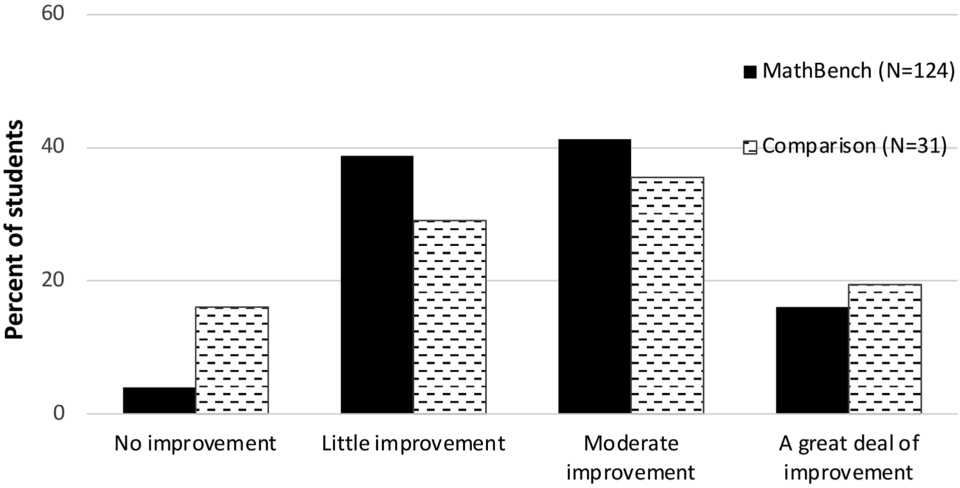
3. *In What Ways Do Students Feel MathBench Impacted Their Learning?*

Ninety-five percent (118 of 124) of students in the MathBench group and 84% (26 of 31) of students in the comparison group perceived at least a little improvement in the quantitative skills over the course of the semester. Within the MathBench group, 50% (62 of 124) indicated that MathBench was most responsible for their gains in quantitative skill, either by itself (40%) or in combination with other course elements (10%). While most students felt that their quantitative skills had improved, student perceptions of the extent of this improvement were uncorrelated with the magnitude of the increase in their scores between the pre- and post-tests of quantitative skill ($F_{3,151}=1.0524$, $p=0.3713$). Additionally, there was no significant difference between MathBench and comparison group students in their perceptions of the change in their quantitative skills ($F_{8,142}=1.1391$, $p=0.3408$, Fig. 4), even though there were clear differences between the groups in the gains measured by the pre- and post-tests (see Fig. 1).

To shed more light on students' perceived benefits from the modules, in the end-of-semester survey, we asked the MathBench group to respond to the open-ended question, "What role did MathBench Biology Modules have in the development of your scientific content knowledge and quantitative skills?" Out of the 124 students in the MathBench group, 70 students (56%) answered this question. Students' responses were grouped under seven themes (Table 2). The most prevalent theme (29 students) was that the modules helped them gain or refresh biological or mathematical content knowledge. One student said, "…It taught me things I didn't know as well as refreshed my memory on things I forgot." Out of the 29 students, 11 students commented specifically on how the modules helped them with statistics in general and probability in particular. As one student mentioned, "The probability module was especially helpful."

In addition to gaining and consolidating content knowledge, 15 students thought that the module developed critical thinking skills such as reasoning and problem solving. As one student said, "I was able to reason better

Fig. 4 Student perceptions of the extent to which their quantitative skills improved over the semester. Students in the MathBench group ($N = 124$) completed MathBench modules as part of their assigned coursework, while those in the comparison group ($N = 31$) did not



and solve problems a lot easier." Other skills that were mentioned were the ability to apply quantitative skills to biology problems and better understanding the relationship between math and biology. As one student wrote, "It helped me figure out how math relates to the field of biology and I was able to figure out situations in the book with ease." Another noted, "I think it explained the scientific content knowledge and quantitative skills in an easy way, so we can apply this knowledge to understand the class material better."

Twelve students explained that the modules provided them with more ways to study beyond the traditional modes of lecture, lab, readings, and homework assignments. As students wrote, "The modules were a helpful supplement to the reading material," "…explained concepts in ways [the] teacher did not," and were "very helpful in terms of practicing mathematical problems and learning new aspects apart from what we learn in lecture/lab." Other students mentioned that the modules provided them with better explanations and summaries of important concepts, as well as "…a

Table 2 Themes, frequencies, and representative responses for the open-ended question *What role did MathBench Biology Modules have in the development of your scientific content knowledge and quantitative skills?*

Theme	Number of students	Representative responses
Gained or refreshed knowledge of biology and/or math	29 (18 general knowledge; 11 specifically referred to probability/statistics)	"A lot of the content was a good review and I think doing them may have helped me score higher on the TEAS test." "It allowed me to calculate probability more easily." "It helped me understand statistical/probability's importance in science."
Developed reasoning, problem solving, and application skills; strengthened the connection between math and biology	15	"I have a better understanding of scientific/quantitative skills/knowledge because of the simplified, comprehensible versions." "Helped me see how and why math is so important for biologists to know."
Provided different ways of learning (e.g., visualization, additional practice solving problems)	12	"It helped by letting me practice different ways of measurement and Punnett squares." "It helped because it had a different approach."
Simplified/made it easy	9	"MathBench was very clear and helpful. It did a great job simplifying concepts."
Created a positive affect	5	"[MathBench played] a story role, I personally really enjoyed them and learned a good bit." "While it was teaching, it was also relaxing & fun."
Helped (no reason)	4	"I really appreciate the probability [module. It] was one of the best one[s] and helped me a lot."
Helped little or not at all	12	"I merely completed the tutorials. Most information contained was already known to me."

Student responses ($N = 70$) could be classified into multiple themes different approach [that] tried to captivate the student more than a regular math class."

Nine students mentioned that the modules "did a great job simplifying concepts," and help them "to understand [the material] easier than just use [of] textbooks," "because [the modules] explain everything step by step". One student explained that.

> The MathBench modules used examples from everyday activities which made the material easy to understand and also there were many examples to practice with. The summary at the end of each topic was also helpful as the important concepts about the topic were made clear and short.

Five students mentioned positive affective experiences with using the modules. They referred to the importance of having "a story role." Students said that the modules were "relaxing & fun," and "…they were cute and not as painful as I thought they were going to be in the beginning of the semester." Four students said that the modules were helpful but did not mention a specific reason.

Finally, 12 students responded that the modules were little help or no help at all in learning course content and quantitative skills. For some, this was because they already knew the information, "…Most information contained was already known to me." Others were confused by the way that the modules were integrated with other assignments, "I found it hard to keep track of when they were due compared to the other quizzes in the assessment list." Some students indicated that the modules were of little help because they did not perceive the application of math to biology as being very important compared to other aspects of the course. One student remarked, "I would prefer to spend time on biology rather than math stuff." Another student mentioned that time constraints led them to prioritize other course content, "…I quickly skimmed through them because of lack of time (more worried about studying the lecture material)."

Discussion

Quantitative skills are vital for biology students heading into the STEM workforce, as employers are increasingly indicating that they value critical thinking and problem solving skills as much or more than technical knowledge (Hart Research Associates, 2015). MathBench was effective in helping community college students improve their quantitative skills and their ability to apply those skills to biological problems. This is consistent with data from introductory biology students enrolled at a 4-year institution (Thompson et al., 2010). MathBench aligns with the recommendations of Vision & Change (AAAS, 2011) in promoting generalized problem solving, real-world applications, and an understanding that disciplines are connected with one another, which are important twenty-first century professional skills.

Improvements were seen across a range of quantitative skills that students encountered in MathBench modules but were often restricted to the easier questions for a particular skill. This is not unexpected, however, since the students were enrolled in their first college-level biology course and the modules assigned were introductions to the topics, as opposed to sophisticated treatments. Interestingly, students seemed to lack metacognitive awareness of their growth in quantitative skill, as student ratings of the extent of their learning were uncorrelated with their gains on the pre-/post-quantitative skills test. Our results are consistent with a growing body of literature indicating that undergraduate students, particularly those who are new to a discipline, are often poor judges of the quality of their own work, but that this is a skill that can be developed with instruction (Boud et al., 2013; Gyamfi et al., 2022; Öhrstedt, 2018).

Qualitative data also supported the value of online, interactive modules such as MathBench in accommodating students with different levels of prior biology knowledge, math preparation, and different learning preferences. We see the modules as a great tool to address this heterogeneity, since they allow students who need more practice and more time exploring the multimedia resources to close gaps in their learning at their own pace, without the instructor needing to take valuable class time for material that some students have already mastered. Students specifically mentioned the value of the modules in providing extra practice opportunities and different kinds of explanations compared to what they encountered in lectures and laboratories.

Our analyses showed no change over the course of a semester in student attitudes about the importance of math in biology or the extent to which they enjoy doing math. This is consistent with previous research indicating that changes in attitudes were only apparent in MathBench users at the time of graduation (Thompson et al., 2013), in accordance with theory suggesting that attitudes develop slowly and are resistant to change (McLeod, 1992). The lack of change in perceptions of the importance of math in this study may be because students' appreciation for the importance of math was quite high from the beginning. In contrast, the extent to which students liked math was fairly low throughout (in roughly the middle of the range of scores) and may be indicative of a substantial number of students who experience math anxiety or discomfort with math. Our findings suggest that the range of attitudes of community college biology students is similar to that of biology students at 4-year institutions. Dethier (2014) found that college biology students believed that math is important to biology, but generally were unsupportive of adding more quantitative content into their introductory biology course. Andrews and Aikens (2018) found that college biology students perceived math as useful to their careers, but substantially costly in terms of the effort required to use mathematics in biology courses. Our work adds to this growing body of literature regarding the ambivalence of biology students towards math.

Although the use of a learner-centered technology (i.e., MathBench) did not significantly shift students' attitudes about math in the short term, our work demonstrates how these technologies can be used effectively to supplement traditional instruction to promote student learning gains. A fruitful direction for future studies is to examine whether these types of resources promote student confidence in their ability to use mathematical approaches in the context of biological sciences. It is important that the relationship between student attitudes and quantitative skills instruction be further explored, as student affect is a significant predictor of achievement and persistence, and student resistance is a potential impediment to the wider integration of quantitative approaches into biology curricula.

Student ambivalence regarding the use of quantitative approaches in biology also highlights the importance of integrating quantitative content into the biology curriculum repeatedly and at all levels, from introductory to advanced, as has been widely advocated (AAAS, 2011; Gross, 2004; Hester et al., 2014). When math content was deeply embedded in an introductory biology course, students showed gains in both quantitative skills and biology content knowledge (Hester et al., 2014), indicating that quantitative proficiency need not be accomplished at the expense of biology content knowledge. Integration of math and biology is necessary to provide students with evidence of the utility of math to biology, which in turn can motivate greater investment in learning quantitative material applicable to biology careers (Aikens et al., 2021).

Limitations and Recommendations

This study was conducted at a single community college. The observed patterns may not be generalizable to other institutions. Of particular concern is the observation that some of the means on the quantitative skills assessment were at or below the level predicted by chance (even on the post-test). It is possible that the level of difficulty of this assessment is not well-matched to the community college context, so the assessment may underestimate changes in quantitative skill.

Because the modules were freely available online and were accessed by students anonymously, it was not possible to know with certainty that only MathBench group students had access to them. Indeed, two of the comparison group students informed us that they used MathBench (and their data was subsequently removed from the analysis). It is possible that our comparison sample still included some students who used MathBench, but if so, this would have rendered our statistical comparisons more conservative (i.e., less likely to detect a difference between the groups).

Qualitative and quantitative findings obtained from this study of community college students were similar in many respects to previous findings from a 4-year university (Thompson et al., 2010), indicating the broad applicability of MathBench modules to improving quantitative skills. There were, however, several distinctions among the studies. Because of institutional differences in pre-requisites for enrollment in biology courses, this study included students with a lower level of math preparation than the previous study. This enabled us to detect the effect of concurrent enrollment in math on improvements in quantitative skill for those with weaker math preparation. In the previous study, students with differing (but higher) levels of math preparation benefited equally from using MathBench, and concurrent enrollment in a math class had no measurable effect (Thompson et al., 2010). This study makes clear the importance of providing less mathematically prepared students with multiple concurrent opportunities to reinforce their quantitative skills.

The magnitude of improvement in quantitative skill observed in the study, though statistically significant, was relatively modest compared to other studies (Thompson et al., 2010, 2013). This might have been due to a lack of sensitivity of the quantitative skills assessment at the lower end of its measurement scale or it might be a further indication that less mathematically prepared students have more trouble transferring their mathematical knowledge to other disciplinary contexts. Self-contained modules, while having many affordances, may not be sufficient by themselves to produce substantial gains. As many have advocated, quantitative content needs to be woven into other aspects of the course, and students need to be accountable for learning the concepts and skills. It is important for students to be getting reinforcement across multiple courses, not only by infusing math into biology courses, but also through the reciprocal strategy of embedding biological content and contexts into math courses designed for biology students (Aikens et al., 2021; Koenig, 2011; Marsteller et al., 2010; Thompson et al., 2013). Instructors should not assume that students, especially those with weaker math preparation, are able to transfer their newly acquired quantitative skills across disciplinary contexts without concurrent reinforcement.

Another difference between the studies was the proportion of students completing both the pre- and post-quantitative skills assessments. This was attributable to comparably fewer students in the community college context staying engaged in the course throughout the semester, leading to fewer students completing both surveys. It was evident from the open-ended comments that some students also did not prioritize the module content because they saw it as being separate from the lecture content and perhaps tangential to the overall goals of the course. Additional research is needed to identify the most impactful ways of employing self-contained modules and maximizing student engagement. Of interest, in this regard, is Karsai et al.'s (2015) description of how MathBench was deeply embedded into in-class and out-of-class activities of an upper-level ecological modeling course, resulting in substantial improvements to student quantitative skills. The relationship between community college student engagement, attitudes towards learning, and academic achievement is complex and therefore warrants further study.

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Author Contribution KVT conceived and designed the analysis, performed the analysis, and wrote the paper; KCN created the modules, contributed analysis tools, and wrote the paper; JS contributed to the development of the modules, collected the data, and wrote the paper; GMA contributed to interpretation of results and wrote the paper.

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Data Availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Ethics Approval Informed consent was obtained from all individual participants included in the study. Subjects provided informed consent regarding publishing their data in aggregate. The study was approved by the University of Maryland Institutional Review Board (Protocol# 09–0510).

Competing Interests The authors declare no competing interests.

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