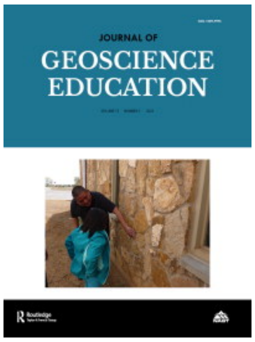

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Using the interactive software FossilSketch to teach micropaleontology to undergraduate students

Anna Stepanova[a], Christina Belanger[b], Saira Anwar[c], Christine Stanley[d], Ankur Nath[a], Josh Cherian[a] and Tracy Hammond[a,e]

[a]Department of Computer Science and Engineering, Texas A&M University, College Station, Texas, USA; [b]Department of Geology and Geophysics, Texas A&M University, College Station, Texas, USA; [c]Department of Multidisciplinary Engineering, Texas A&M University, College Station, Texas, USA; [d]Department of Educational Administration and Human Resource Development, Texas A&M University, College Station, Texas, USA; [e]Institute for Engineering Education and Innovation, Texas A&M University, College Station, Texas, USA

ABSTRACT

Micropaleontology is a critical tool for determining the ages of geologic records, reconstructing ancient environments, and monitoring modern ecosystem health. However, most students are not exposed to micropaleontology in their college coursework. To enable non-expert instructors to integrate microfossil identification training in their undergraduate courses, we developed FossilSketch, an interactive web-based educational tool that introduces students to the basics of micropaleontology and guides students through a scaffolded learning experience that develops microfossil identification skills. Here we test the impact of FossilSketch on students' ability to learn micropaleontology skills, such as identification of microfossils to genus level and basics of fossil data analysis, using data on students' performance and survey responses collected in an undergraduate paleontology course for geology majors at a large public university. A total of 112 students took part in this study. Analysis of classroom assessments showed that junior and senior geology majors who used FossilSketch were better able to understand the process of microfossil identification, recognize morphological characteristics, and achieve a correct identification than those who did not use FossilSketch. Students who used FossilSketch needed to ask the teaching assistant fewer questions and felt better prepared for specimen-based work than students who did not use FossilSketch. These results suggest that FossilSketch improves students' understanding of the microfossil identification process.

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Taxonomy; micropaleontology; undergraduate education

Introduction

Micropaleontology is the study of fossils that are typically a millimeter or less in size. These microfossils are preserved in sediments deposited in ocean basins and lakes and are important for determining the ages of geologic records, reconstructing ancient environments, and monitoring modern ecosystem health (Jones, 2013; Murray, 2006; Capotondi et al., 2015). However, training undergraduates to identify microfossils is time-intensive due to the use of microscopes and the amount of individual feedback required from the instructors to students, and most students are not exposed to micropaleontology in their courses (Tewksbury et al., 2013; Armstrong & Brasier, 2013), which limits the number of students having necessary exposure for careers in domains using microfossils. To enable non-experts in micropaleontology to integrate microfossil identification training in their undergraduate courses, we developed FossilSketch, an interactive web-based educational tool that introduces students to the basics of micropaleontology and guides students through a scaffolded learning experience that develops microfossil identification skills.

FossilSketch is a sketch-based intelligent tutoring system. Intelligent tutoring systems are educational software that can provide feedback and track student work. It is free, web-based, platform-independent and accessible from any device that has an internet connection, such as a tablet, laptop, or desktop computer. No additional training is needed for instructors to use FossilSketch. FossilSketch educational modules were based on an existing specimen-based laboratory curriculum used at Texas A&M University and micropaleontological datasets created by the principal investigators (Belanger & Stepanova, 2023). It includes four modules: educational videos, mini-games, genus identification exercises, and assemblage exercises. FossilSketch focuses on two groups of microfossils: Foraminifera and Ostracoda. Foraminifera and Ostracoda are commonly used microfossils with industrial, environmental, and scientific applications. These are also some of the larger microfossils, making them accessible for student viewing with standard stereoscopes. Foraminifera are protists with a calcareous shell that are often abundant in marine environments (Armstrong & Brasier, 2013). Ostracoda are microcrustaceans with a bivalved calcareous carapace that are found in all aquatic

CONTACT Anna Stepanova anna_stepanova@tamu.edu Department of Computer Science and Engineering, Texas A&M University, College Station, Texas, USA.
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environments from freshwater lacustrine to deep-sea marine systems (Smith & Delorme, 2010). The morphology of benthic Foraminifera and Ostracoda is closely related to the environments in which they live (Frenzel & Boomer, 2005; Jorissen et al., 2007) and, Foraminifera in particular are often used in geochemical studies (Holbourn et al., 2014).

In FossilSketch, students watch educational videos focused on microfossil applications in geosciences, characteristic morphological features, and the process of genus-level identification for benthic Foraminifera and Ostracoda (Belanger et al., 2020a; Stepanova et al., 2020; Belanger et al., 2020b; Belanger & Stepanova, 2023). Then, students practice recognizing morphological features through mini-game activities that divide the identification process into smaller tasks, before combining their microfossil identification skills to fully identify common genera from high-resolution photomicrographs. After learning to identify microfossils, students apply this knowledge to multispecies assemblages and make interpretations about the environment the assemblage represents. This final module simulates what an investigator using microfossils as a tool would accomplish. Because the tool provides a scaffolded learning experience to develop microfossil identification skills by gradually increasing the difficulty of exercises, students can gradually build confidence in working with microfossils. Further, FossilSketch allows students to practice these skills anywhere with internet access using a tablet or personal computer and to receive real-time feedback without instructor supervision to help learners deepen their understanding.

We hypothesized that students who completed the FossilSketch exercises would be more successful in identifying microfossils, would use a more evidence-based approach in the identification process, and would feel more engaged than students who learned the same content without FossilSketch

Overall, our learning goals are to increase student comprehension and retention of micropaleontology knowledge and student engagement with the analysis and application of micropaleontological data. After completing FossilSketch activities, participants should be able to understand the main applications of microfossils in geoscience research and industry, as well as steps in the identification process of Foraminifera and Ostracoda to genus level, and basics of fossil data analysis.

Relevant and theoretical underpinning

Overview

The geosciences have rapidly adopted online and remote-based educational tools over the last ten years, and the popularity of online learning platforms has led to the development of new online resources, pedagogical practices, and course curricula (e.g., Bralower, 2017; Bravo, 2017; Brande & Nosofsky, 2022). Instructors have successfully integrated high-resolution digital imaging for mapping and documenting geological outcrops, 3D virtual simulations, and digitization of fossil collections into their in-person courses as well (Bentley, 2017; Cawood & Bond, 2019; Hughes et al., 2017; Bursztyn et al., 2017). A workshop on "Teaching about Earth Online" called for the need to develop best practices for online Earth science education (Penn State, 2017), and a literature review suggests that these virtual learning environments must incorporate both immersion and interaction to be effective (Carabajal et al., 2017). Further, the last two decades of inclusive geoscience education research have called for the development of accessible laboratory- and field-based curricula at the introductory level. Thus, designing novel, accessible online, and academically rigorous educational tools, like FossilSketch, is relevant to advancing undergraduate geoscience education.

It is noteworthy that gamification holds significant potential in geoscience education, offering new avenues for engaging students, promoting active learning, and fostering a deeper understanding of geological concepts. Gamification, game-based learning, or serious games are often shown to be more effective than traditional educational methods in terms of learning and retention (Wouters et al., 2013), motivation and engagement (Williford et al., 2017), and behavioral learning outcomes (Sailer & Homner, 2020). Educators have explored how gamification can enhance learning experiences in geoscience education through digital and board games (e.g., Spandler, 2016; Cartier, 2018a, 2018b; Martindale & Weiss, 2020). Game elements such as simulations, virtual field trips, and interactive quizzes are integrated into the curriculum to create immersive and experiential learning environments and offer the advantage of being available outside of the classroom and providing feedback in real time.

Successful implementation of software in geoscience education includes sketching software, virtual microscopes, and field experience simulations. CogSketch is a sketching-based application with a series of 26 introductory geoscience worksheets about key geoscience concepts (Forbus et al., 2017). CogSketch aids students in solving discipline-specific spatial problems while providing instructors with insights into student thinking and learning. Real-time feedback identifies erroneous sketch features and helps students reconsider and correct them. A "virtual microscope" developed by Milliken and coauthors allowed geology students to practice identification of a wide array of sandstone components outside of the laboratory and independent of the instructor. Use of the software and tutorials demonstrably improved the students' petrography skills (Milliken et al., 2003). Virtual reality field trips aimed at teaching spatial skills allowed students to obtain a general overview of the area and obtain background information in an interactive three-dimensional model that enabled them to maximize their experience when in the field (Arrowsmith et al., 2005). Further, augmented reality field trip games for smartphones and tablets significantly increased student interest in learning sciences (Bursztyn et al., 2017).

In the field of paleontology, researchers note a decline in micropaleontology training and subsequent lack of human experts (Carvalho et al., 2020; Hsiang et al., 2019; Mitra et al., 2019). However, most software development to fill this gap in expertise has been aimed at computer-automated identification of microfossils. The earliest attempts lacked accuracy and were not fully automated (Athersuch et al., 1994; Ranaweera et al., 2009), thus microfossil experts were still required. More recent approaches to automated microfossil identification software focuses on machine learning and use 3D models for identification (Carvalho et al., 2020; Hsiang et al., 2019; Mitra et al., 2019); these systems perform identifications comparably to human experts (Mitra et al., 2019). Other efforts focus on increasing human knowledge through large microfossil databases that include taxonomic hierarchy data, images, ecological characteristics, and geographical distribution, as well as type species information (e.g., for Ostracoda: Modern Podocopid Database (Cronin et al., 2010); World Ostracoda Database (2022); for Foraminifera: World Foraminifera Database (2022); Foraminifera Gallery (2022); Mikrotax.org (2022)). However, these online resources are designed for advanced users. They are challenging to use for entry-level professionals and students without instruction on microfossil morphology, leaving a need for an introductory-level tool like FossilSketch.

Theoretical framework

The cognitive aspect of the constructivist framework guides the theoretical underpinning of FossilSketch development and implementation. The premise of FossilSketch is to provide students with interactive, hands-on learning experiences and learning through discovery and interactive exercises. These features of FossilSketch align with the principles of discovery learning (Bruner, 1966) and learning by doing approach (Dewey, 1916). Discovery learning suggests that students learn effectively when they discover concepts independently and are not given guidance and knowledge in lectures only. This theory encourages approaches that promote exploration, experimentation, asking questions, and seeking answers. FossilSketch is designed to help students discover conceptual knowledge about microfossils through experimentation and games, emphasizing the importance of inquiry-based learning (Fincher, 1985). It allows students to construct new ideas and concepts based on their ability to connect with present and past knowledge (Bruner, 1966). The theorists agree that learning by doing allows students to improve comprehension (Dewey, 1916). This implication suggests that students should have sufficient opportunities to practice and perform. FossilSketch was designed to promote students' engagement with the interactive learning process, thus ensuring a hands-on experience.

Fossilsketch interface overview

Landing page

FossilSketch software is available free of charge at fossilsketch.org. The title page provides a link for instructors to request access to the website. The video linked on the same page gives an overview of the FossilSketch interface, its main activities, and exercises. Suggested lesson plans are available through the National Association of Geoscience Teachers' Teach the Earth website (Belanger & Stepanova, 2023). After the participants log in, they see a landing page with modules listed in the order in which they are meant to be completed (Figure 1).

Educational videos

Educational videos provide introductory information on microfossil morphology and applications. All educational videos embedded in FossilSketch are publicly available on YouTube and have captions. In this study we used three videos, describing: 1) the various applications of microfossils in research and industry (Belanger et al., 2020a), 2) the basics of Ostracoda (Stepanova et al., 2020), and 3) Foraminifera morphology and terminology (Belanger et al., 2020b). The videos do not replace lecture materials but provide necessary information for students to engage with the games and exercises in FossilSketch and with the microfossil laboratory activities using microscopes and slides with foraminifers or ostracods.

Mini-games

FossilSketch mini-games aim to improve student comprehension of microfossil identification by dividing the identification process into smaller tasks. FossilSketch currently has four mini-games: Ostracoda outlines (Figure 2), Ostracoda valve orientation (Figure 3), Foraminifera morphotypes (Figure 4), and Foraminifera chamber arrangements (Figure 5). For all games, students receive star ratings from zero to three based on how many rounds they completed correctly on the first attempt. In all the mini-games, students could advance to the next round only by submitting a correct answer.

The Ostracoda valve outline game helps students practice the identification of the three major types of lateral outlines of ostracod valves: subrectangular, subtriangular, and oval or bean-shaped. Before the beginning of the game, a student views an image with four ostracod valves, and the adjectives we use to describe them, such as subtriangular, oval, or bean-shaped are explained (Figure 2(A)). Then the student needs to match the three outline images with the three different, randomly-selected images of ostracod valves from the FossilSketch database (Figure 2(B–D)). There are three rounds in this game. If the answer is incorrect, FossilSketch provides a hint by showing the geometrical shape that is most similar to the pictured valves, as seen in Figure 2(C).

The Ostracoda valve orientation game helps students learn about the basic morphology of ostracod valves by asking them to orient the valve with the dorsal side up. At the beginning of the game, the student reviews an image of an ostracod valve with the four margins (anterior, posterior, ventral, and dorsal) labeled (Figure 3(A)). In each round of the game, the student rotates an incorrectly oriented ostracod valve into the correct orientation by clicking on it. When the student submits their answer, FossilSketch marks them as correct or incorrect (Figure 3(B–D)). If incorrect, FossilSketch provides a hint as to how to orient it correctly, such as "The valve's outline is usually elongated, with the

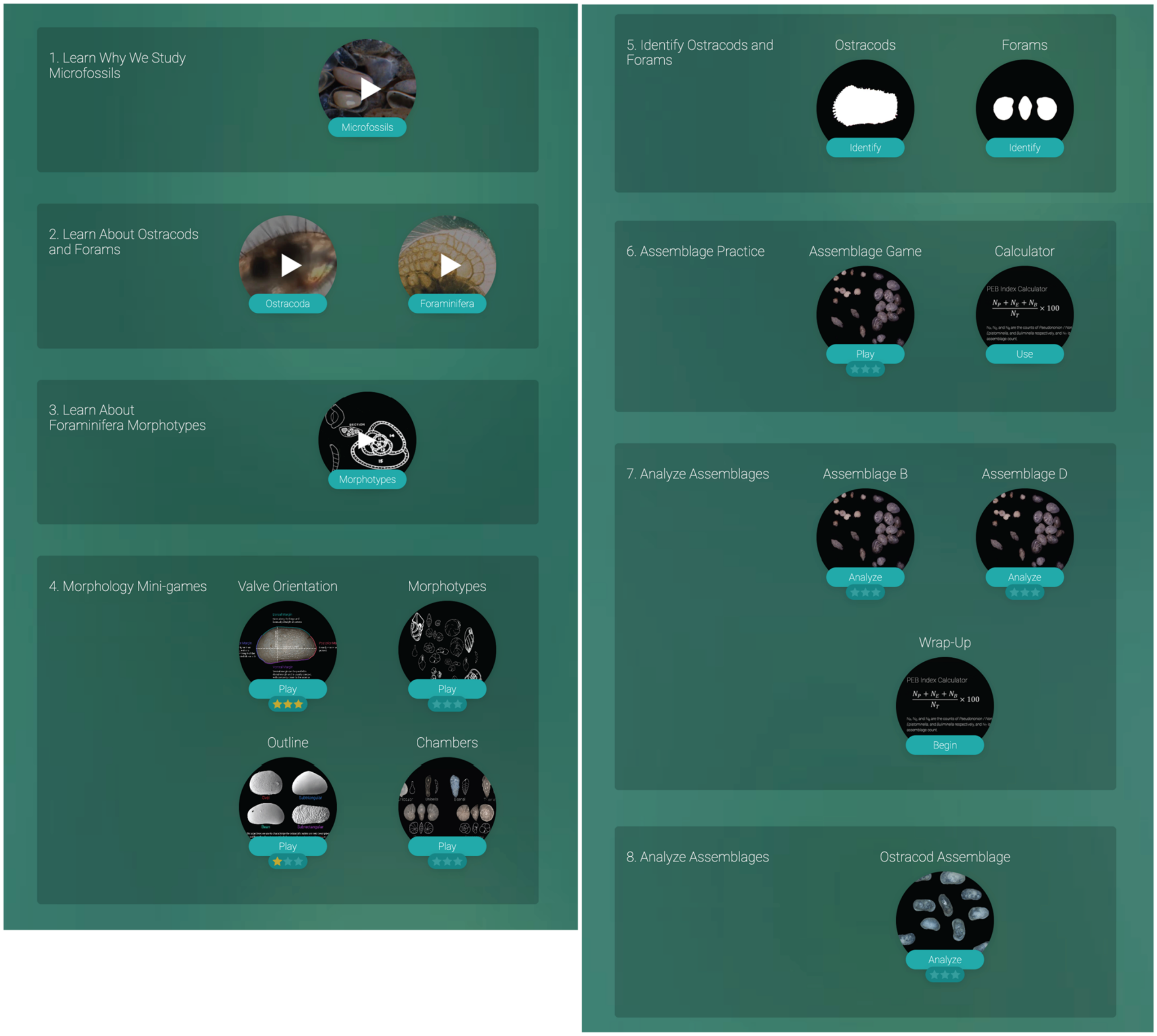

Figure 1. FossilSketch landing page. Sections: 1-3—educational videos; 4—mini-games; 5—genus identification; 6—assemblage practice game; 7—foraminifer assemblage exercise based on the Gulf of Mexico material; 8—ostracod assemblage exercise based on the Baltic Sea material.

maximum length subparallel to the ventral margin" as seen in Figure 3(C). A student can then submit a revised answer.

The Foraminifera morphotypes game presents a simplified way to categorize Foraminifera based on their overall test shape. At the beginning of the game, the student reviews an image with eight possible Foraminifera morphotypes (Figure 4(A)). For each round of the game, Foraminifera images are randomly drawn from the database, and students are asked to match the image with the correct morphotype (Figure 4(B, C)). The first round has four images to match, and this increases to six and eight images in rounds two and three, respectively. FossilSketch provides feedback by indicating which images were matched incorrectly and allows the student to submit a revised answer as seen in Figure 4(D).

The Foraminifera chamber arrangement game is also a matching game. At the start of the game, the student reviews an image with the six possible chamber arrangements (Figure 5(A)). For each round of the game, four Foraminifera images are randomly drawn from the database and students are asked to match the images to the correct chamber arrangement type (Figure 5(B, C)). FossilSketch provides feedback by indicating which images were matched incorrectly and the student can submit a revised answer as seen in Figure 5(D).

Genus identification exercises

For identification of Ostracoda genera, four identification steps are included in FossilSketch: 1) sketch the maximum length and height of the valve and identify the right vs. left valve (Figure 6(A, B)); 2) sketch the outline of the ostracod valve and choose the type of outline from the menu (Figure 6(C, D)); 3) measure the approximate size of the valve and choose the size group from the menu (Figure 6E); 4) choose ornamentation features if present Figure 6(F).

For identification of Foraminifera genera, six steps are included in FossilSketch: 1) sketch the outline of the

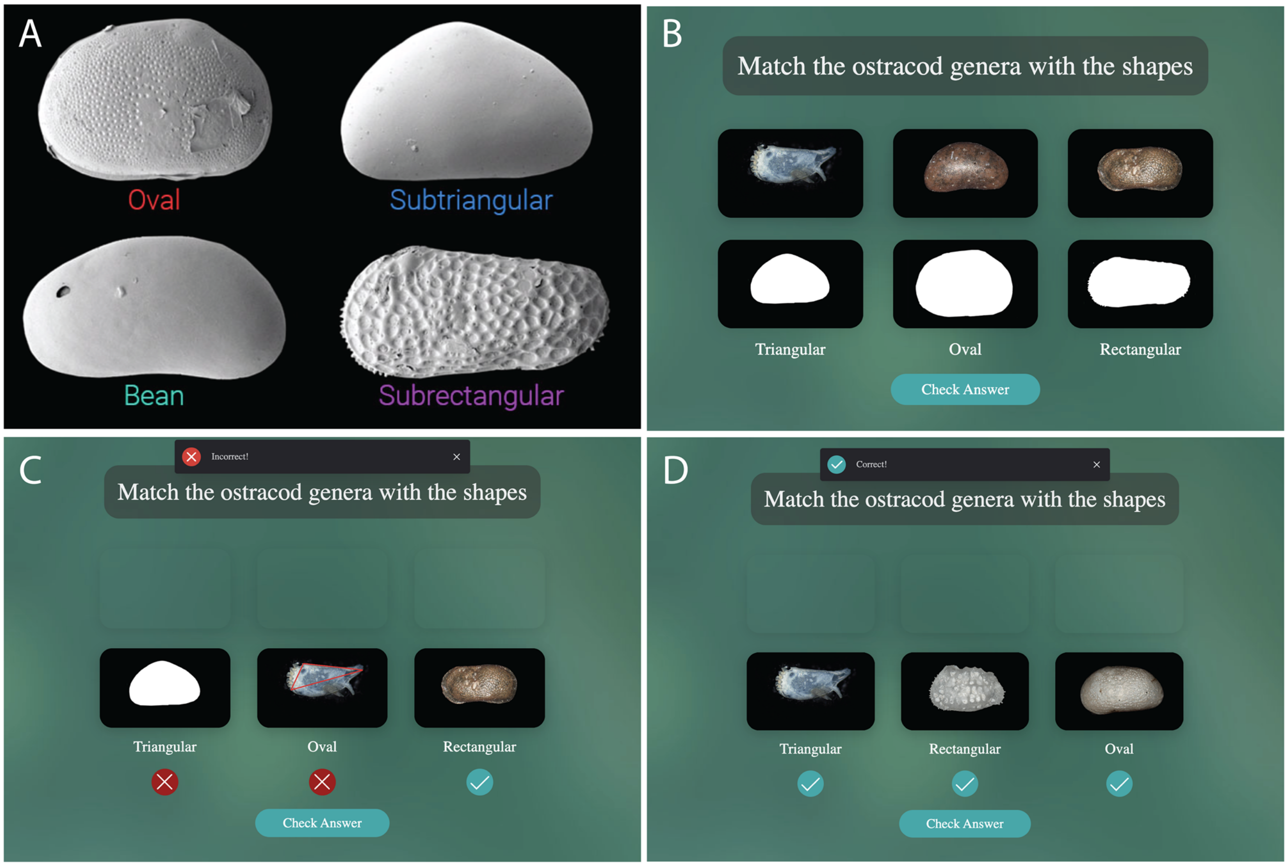

Figure 2. The Ostracoda valve outline mini-game: (A) Reference images of ostracod valve outlines; (B) View of the screen at the beginning of the game; (C) FossilSketch provides a hint by showing what geometrical shape the valves are closest to; (D) Correct answers are submitted.

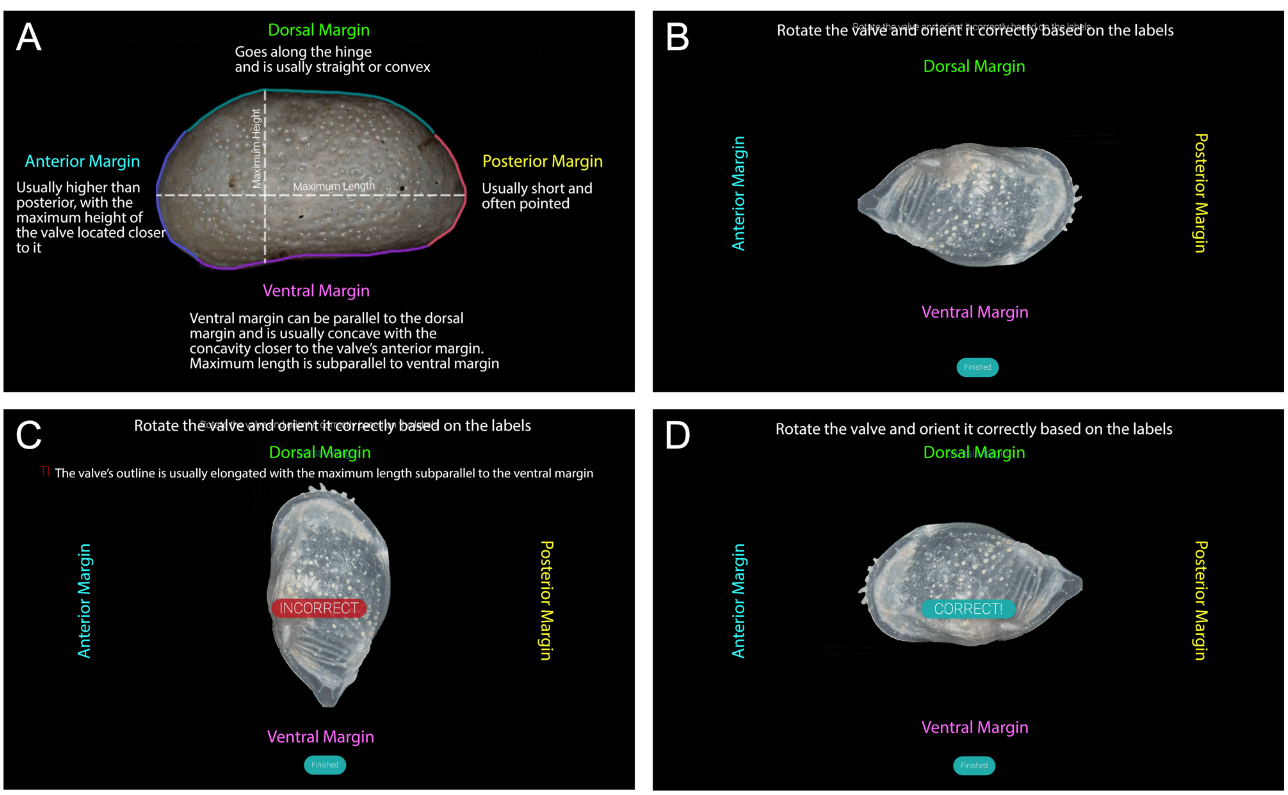

Figure 3. The Ostracoda valve orientation mini-game: (A) Reference image with a general description of an ostracod valve, with the four margins, anterior, posterior, ventral, and dorsal labeled; (B) View of the screen at the beginning of the game; (C) FossilSketch provides a hint on how to orient the valve correctly; (D) The valve is oriented correctly.

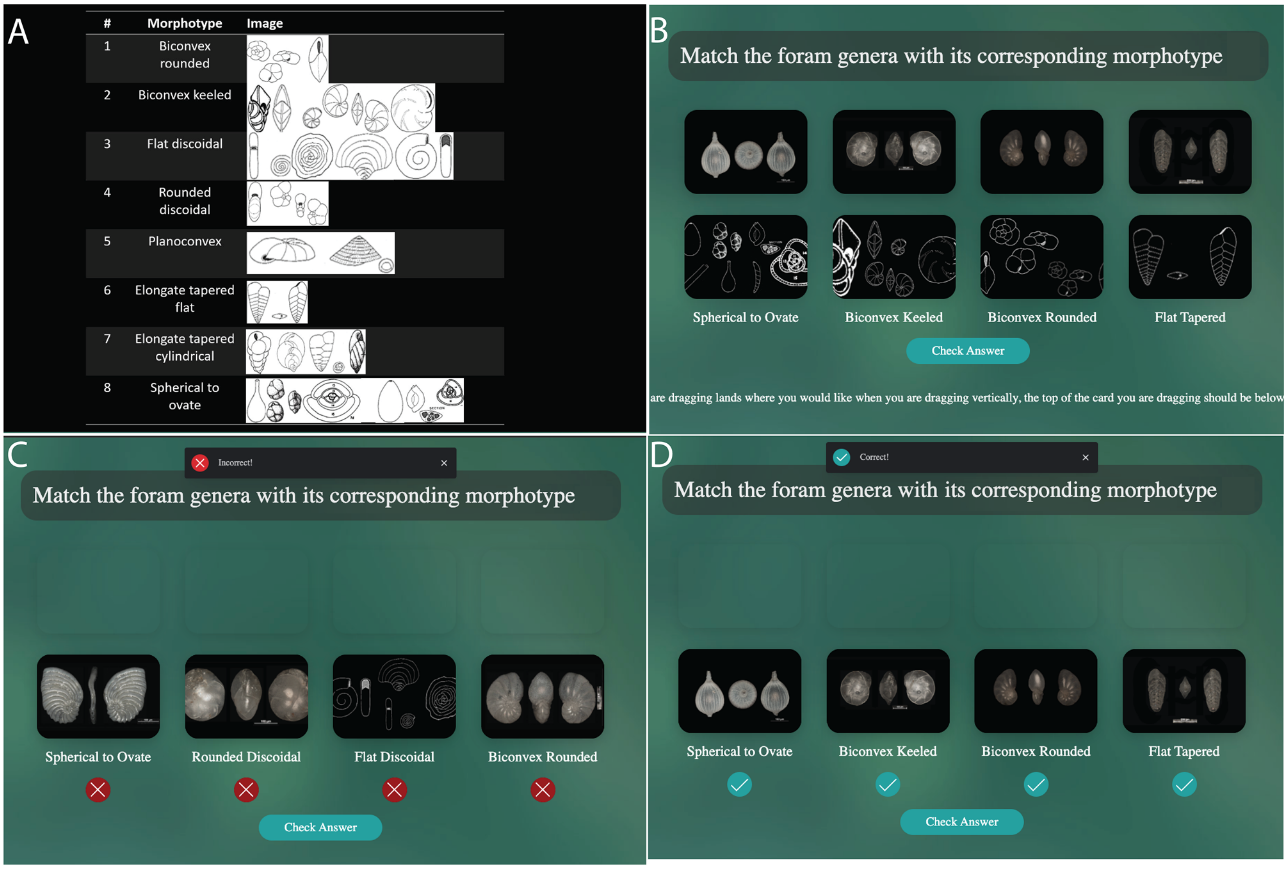

Figure 4. The Foraminifera morphotypes mini-game: (A) Reference image with the eight Foraminifera morphotypes; (B) View of the screen at the beginning of the game; (C) FossilSketch provides feedback by showing what answers are correct and incorrect; (D) Correct answers are submitted.

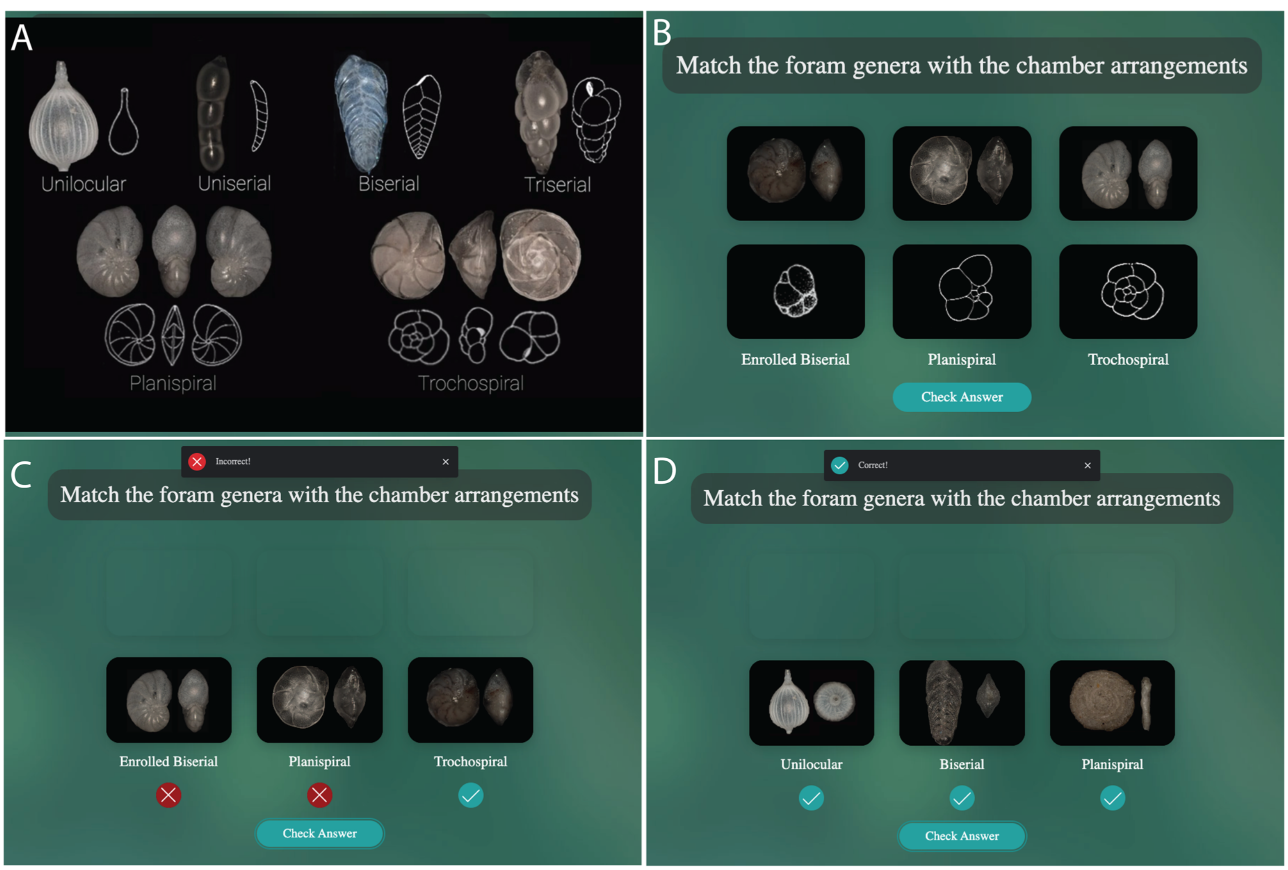

Figure 5. The Foraminifera chamber arrangement mini-game: (A) Reference images of the six types of foraminifer chamber arrangements; (B) View of the screen at the beginning of the game; (C) FossilSketch provides feedback by showing what answers are correct and incorrect; (D) Correct answers are submitted.

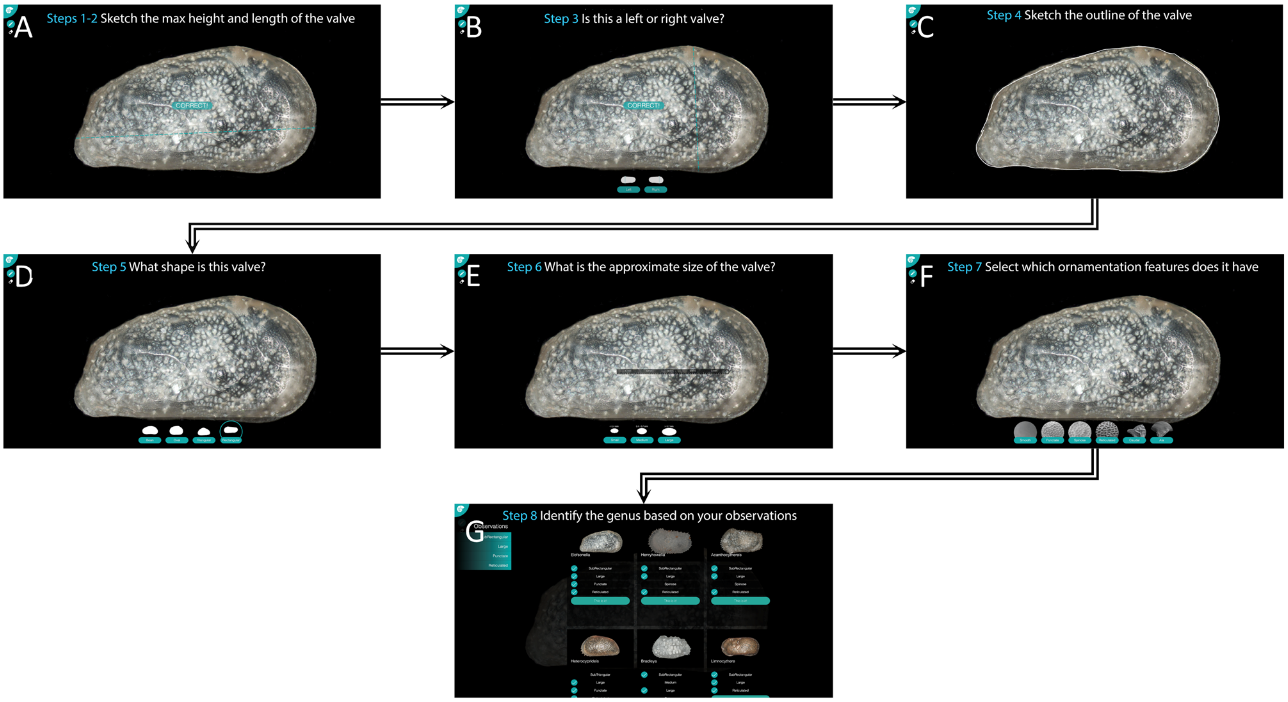

Figure 6. Ostracoda genus identification steps. (A, B)—Steps 1-3. Sketch the maximum length and height of the valve and identify if it is a right or left valve; (C, D)—Steps 4-5. Sketch the outline of the valve and select the type of outline; (E)—Step 6. Estimate the size of the valve; (F)—step 7. Select which ornamentation features does it have; (G)—Step 8. Identify genus from the database sorted by the number of correct features selected by the user.

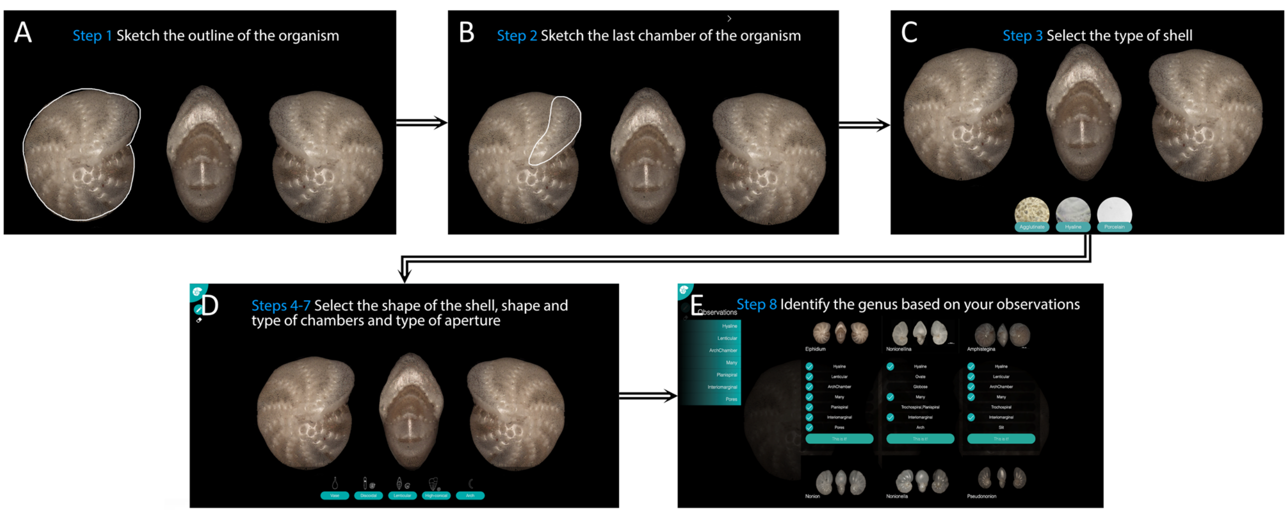

Figure 7. Foraminifera genus identification steps. (A, B)—Steps 1-2. Sketch the outline of the shell and of the last chamber; (C)—Step 3. Select the type of shell; (D)—Steps 4-7. Select the shape, chamber shape, number of chambers and chamber arrangement, the type and location of the aperture; (E)—Step 8. Identify genus from the database sorted by the number of correct features selected by the user.

foraminifer image, then sketch the outline of the foraminifer last chamber (Figure 7(A, B)); 2) choose the shell wall material this foraminifer has (Figure 7(C)); 3) choose the overall shape of the test (Figure 7(D)); 4) choose the chamber shape and how many chambers it has; 5) choose the chamber arrangement; 6) select the location of the aperture and its shape. On Figure 7(D), steps 3-5 are not shown separately, since all three have a similar menu and display.

For both Foraminifera and Ostracoda (Figures 6(G), 7(E)), the last screen shows all the morphological features selected by the user on the left-hand side as *Observations*. The images are sorted by the number of correctly selected features. If the student's answers are correct, the identification is straightforward and is the first in the list of images (Figure 7(E)). If the answers are incorrect, the student will see the list of correct features under the image they just identified and can identify their errors.

Assemblage exercises

In micropaleontology, microfossils are picked from sediment samples and taxonomically identified to characterize whole assemblages of fossils, which are used to interpret past environments. In the assemblage exercises in FossilSketch, students use microfossils to reconstruct aspects of the environment in which the organisms lived, such as salinity and oxygenation. For the exercises we used real fossil assemblages from the Gulf of Mexico (Payne, 2021) and the Baltic Sea (Stepanova et al., 2019). These interactive exercises integrate ecologically-relevant concepts and allow beginners to develop the skills necessary for making rapid environmental assessments from fossil data.

FossilSketch offered two assemblage exercises using Foraminifera from the Gulf of Mexico. In the first one, students practiced identifying foraminifer specimens from the three assemblages, each comprised of 20 specimens (Figure S1). These assemblages imitate an actual microfossil assemblage slide as seen under a microscope. In each of the four rounds, students identify the genera present, count how many individuals of each genus are present, and tabulate their results using a menu on the right side (Figure S1 A). If the submitted answer is incorrect, FossilSketch highlights the genera in the menu that are present in the assemblage, and the student can submit a revised answer (Figure S1 B). The second assemblage exercise aimed to assess the oxygenation history of the Texas (U.S.A.) continental shelf (Payne, 2021). When working on this exercise, students review provided background environmental information on the Gulf of Mexico region and the use of benthic foraminifera to reconstruct the oxygenation history of the Texas shelf *via* the PEB (*Pseudononion*, *Epistominella*, *Buliminella*) and A-E (*Ammonia-Elphidium*) indices, which are calculated from the relative abundances of foraminifera species that are sensitive to oxygen changes (Osterman, 2003; Gupta & Platon, 2006) (Figure S2 A). Students explore two samples, each of which is comprised of multiple images showing different species of Foraminifera (Figure S2 B, C). Students identify the Foraminifera to genus and input the number of specimens they see of each genus using the menu on the right side of the screen. The menu on the right includes six key Foraminifera species, and the rest are grouped under the category "other." When the student submits an answer, FossilSketch shows if the count is correct or incorrect, and then proceeds to the next image even if the answer was incorrect. The last screen of the exercise shows a calculator with the student's counts and the calculated PEB and A-E indices (Figure S2 D). Students then infer the relative oxygenation of the two samples. For both exercises, students draw on their knowledge from the previous exercises to identify the Foraminifera genera.

The Ostracoda assemblage exercise is based on the Baltic Sea material from IODP Exp. 347, with three assemblages corresponding to alternating environmental phases characteristic of its Holocene history (Stepanova et al., 2019). The Baltic Sea region has experienced several climate-driven hydrological changes during the Holocene resulting in alternating freshwater and brackish phases (Andrén et al., 2011). In this exercise, students learn how to use the abundance of ostracods that prefer a different range of water salinity to infer past bottom water salinity.

Before students start working on the exercise, they view a screen with information on the Baltic Sea region, its geological history, and the use of Ostracoda for paleoreconstructions (Figure S3 A). Then students go through three samples or slides with ostracods where they count and submit the number of specimens of different genera in the menu on the right side (Figure S3 B). The menu to select from includes the genera that are and are not present in the assemblage. If a student submits an incorrect answer, FossilSketch provides feedback by showing the same image with all ostracods labeled (Figure S3 C), so a student can review and submit a revised answer. The last page is a summary that shows all correct answers and the ostracod types in relation to salinity for each of the three samples, and a student is asked to make an overall conclusion about the water salinity based on these assemblages (Figure S3 D).

Methods

This study used a multi-method research design, where data were collected and analyzed using quantitative and qualitative approaches. For students' performance data, we followed a quasi-experimental research design and measured how much student comprehension of micropaleontology knowledge increased (or decreased) after using the sketch-based intelligent tutoring system FossilSketch. We assessed student learning using their answers to the laboratory assignment and laboratory practical quiz questions. More specifically, we followed the nonequivalent control group design (Campbell & Stanley, 2015), where control and test groups were naturally assembled in the courses where data were collected.

Using students' performance data on two classroom assessments, we evaluated students' learning and assessed the following research questions:

- RQ1: Did students in the test group achieve higher weighted scores on the lab assignment than in the control group?
- RQ2: Did students in the test group score higher than those in the control group on the lab practical quiz at the end of the term?

To describe students' learning we also examined students' perceptions on their FossilSketch experience and how they used strategies to mitigate difficult situations, using survey data. For survey analysis, we followed the principles of inductive thematic analysis, which is a data driven process of coding without fitting into a preexisting coding frame and researchers' preconceptions (Braun & Clarke, 2006).

- RQ3: What are students' perceptions on FossilSketch experience and their mitigation strategies to handle difficulties?

Study participants

Students in the Texas A&M University Department of Geology and Geophysics course Paleontology and Geobiology (Geol 314) were invited to participate in the study. Students in Geol 314 were primarily junior and senior undergraduates majoring in Geology. Lecture class sizes ranged from

Table 1. Data collection conditions.

Semester and Class	Spring 2020 (Control)	Spring 2021 (Test)	Spring 2022 (Test)
Instructor	Expert	Not present	Not present
TAs	Experts	Novices	Novice
Mode	In-person	Hybrid	In-person, but 1 section had a lab remotely
Lecture on microfossil morphology and applications (50 min)	In-person	*via* Zoom	In-person
Students reviewed two morphology supplements before the laboratory session	Yes	Yes	Yes
FossilSketch access	None	Before and during the laboratory session	Before and during the laboratory session
FossilSketch feedback	No	Feedback only for genus ID	Most of the activities had feedback
Lab assignment (genus identification)	Using slides and specimens in the lab	Online or using slides and specimens in the lab	Online or using slides and specimens in the lab
Lab practical quiz	Yes	Yes	Yes
Microfossil Assemblage study	Using microscopes and slides	Removed	In FossilSketch
Duration of instruction	Lecture – 50 min Laboratory with TA- 3 hrs FossilSketch - not available	Lecture – 50 min Laboratory with TA- 1 hr FossilSketch videos – 20 min	Lecture – 50 min Laboratory with TA- 3 hrs FossilSketch videos – 20 min

Table 2. Study participants and types of data collected.

Semester and Class	Spring 2020 (Control)	Spring 2021 (Test)	Spring 2022 (Test)
Total number of students in the class	60	48	43
Students who consented to participate	51	26	35
Demographic survey	25	25	35
Engagement survey	25	23	26
Focus group students	51	not collected	35
Genus ID/lab assignment, Ostracoda	10	11	13
Genus ID/lab assignment, Foraminifera	34	11	19
Lab practical	49	22	35

The reported number of submissions for each category of data only includes participants who consented to participate in our study.

Table 3. Demographic data.

	Control group 2020	Test group 2021	Test group 2022
Number of participants who consented	25	25	35
Gender			
Male	14	12	15
Female	11	12	19
Average Age	21	21	25
Highest degree achieved by a parent			
Bachelor's Degree	17	10	14
Master's Degree	8	9	10
PhD	0	1	2
High school	4	6	3
Associates Degree	1	3	3
Did not complete high school	1	0	3
Year in school			
3rd	9	14	1
4th	14	9	22
5th	2	2	1
Ethnicity			
White	15	15	29
Hispanic	5	5	4
Asian	3	3	1
Black	2	0	0

40-60 students and laboratory sections ranged from 10-22 students. Before data collection and using FossilSketch software, participants were given a quick overview of the project and signed consent forms (IRB2019-1218M, expiration date 02/09/2023).

A total of 112 students and three TAs consented and took part in the study, of which 51 students represent the control group, and 61 represent the test group (Table 1). Table 2 shows the summary of the data types we collected in this study, which include demographic and engagement surveys conducted at the same time, a genus ID exercise, a lab practical quiz, and focus group data. All data were collected and anonymized by the IRB-approved researchers and graduate students on this project before the instructor of the class had access to the final set of data for analysis.

The response rate for the demographic survey was 49% for the control group. It was comprised of 56% males with average age of 21. 60% were White, 20% were Hispanic, 12% were Asian, and 8% were Black or African American. Participants were in their 3rd (36%), 4th (56%), and 5th (8%) year of school. Most participants had parents whose highest degree was a Bachelor's (68%) or a Master's degree (32%). For the test group, the response rate for the demographic survey was 96%. It was comprised of 43-48% males with average age of 21 in 2021 and 25 in 2022. 60-82% were White, 12-20% were Hispanic, and 4-12% were Asian. Participants were in their 3rd (2-35%), 4th (36-62%), and 5th (4-8%) year of school. Most participants had parents whose highest degree was a Bachelor's (40%) or a Master's degree (29-36%). The majority (80-85%) of participants in both groups, control and test, did not have any prior experience in micropaleontology (Table 3).

FossilSketch intervention

As our intervention we used the FossilSketch application. The control group is represented by students in 2020 who did not use FossilSketch. The test group includes students who used FossilSketch in 2021 and 2022.

In 2020 (control group), students had one in-person 50-minute lecture session on the morphology and environmental interpretation of microfossils, with an emphasis on Foraminifera, before the laboratory session. In 2021 (test group), the lecture was delivered *via* Zoom, but otherwise, students had the same lecture experience. In 2021, students had access to FossilSketch before the laboratory session and were expected to complete the FossilSketch activities before attending their laboratory session. In 2022 (test group), the lecture was in person. Students were given time during the laboratory session to complete the FossilSketch activities but were asked to watch the videos before attending the lab, with a total duration of 20 min for all three videos. In all three years, students were asked to complete a reading assignment that included a brief description of the use of Foraminifera in paleoclimate studies that has an emphasis on planktonic groups (which are not covered by FossilSketch). Students were also asked to review two morphology supplements pertaining to Foraminifera and Ostracoda before their laboratory session (Table 1).

Table 1 summarizes the data collection conditions between the three years. In 2020, two graduate student teaching assistants (TAs) with expertise in Foraminifera led laboratory instruction, and two faculty instructors, experts in micropaleontology, were present for the in-person laboratory session. In 2021 and 2022, the graduate teaching assistants were not experts in micropaleontology, and no faculty instructors were present during the laboratory session. COVID-19 instructional modifications allowed students to elect to complete the laboratory in-person or remotely in 2021 and 2022. FossilSketch in 2021 had automated feedback only for the genus identification exercise, whereas mini-games and assemblage exercises did not provide feedback, and students had to repeat activities on their own to get the correct answer. In 2022, new feedback was added, which included showing the correct counts for assemblage exercises. Descriptions of the mini-games and exercises below include additional automated feedback that was added after data collection and student comments.

In 2020 TAs were present in the lab session for three hours. They introduced the assignment, provided reminders, and reviewed key terminology. In hybrid teaching mode in 2021, students had access to the TAs in small groups, where they were only available for 1 h during the lab session. In 2022, students in the in-person lab session had access to a TA the full three hours. One of the sections in 2022 was canceled due to a storm, and students completed the assignment remotely without TA access but could visit the TA during office hours or request an in-person make up. With the exception of 2020, the TAs were non-experts and were guiding and facilitating more than teaching.

Evaluation design and data collection protocol

During the experiment, we collected survey and focus group data *via* classroom assessments. These data reflect students' perspective on using FossilSketch and their performance in micropaleontology. Data collection protocols were the same for control and test conditions (Table 1). After students reviewed and signed the consent forms, they were asked to complete the demographic surveys. The microfossil laboratory was the third laboratory assignment students complete each year and occurred from late January to early February in all three years. Students worked on the lab assignment during the microfossil laboratory. The engagement survey included questions where students could reflect on their learning, challenges and how they were mitigated. In this study, engagement is a measure of a student's level of interaction and involvement with the micropaleontological material in the lab, which can help students become successful learners in micropaleontology. Our definition involves behavioral and cognitive dimensions of engagement (LaDue et al., 2022). Two weeks after the micropaleontology laboratory session, students completed the engagement survey and participated in a focus group (the latter only in 2020 and 2022, See Supplement 1, Table 2). Students who consented to be in the study participated in focus groups, conducted by graduate students. Focus groups had between 11 and 17 students per group and were audio recorded and transcribed. Approximately three months after the laboratory session, students completed a laboratory practical quiz (Table 2). In the control year, five students took the laboratory practical quiz who did not complete the laboratory assignment. Similarly, four more students completed the laboratory practical quiz than the laboratory assignment in the two test years combined.

Data collection and analysis

During the 2020 laboratory session (control group), all students completed specimen-based laboratory activities by rotating through stations with physical materials (Table 1). The laboratory session was three hours long. For the Foraminifera, these activities included examining enlarged 3D physical models of Foraminifera (Miller, 2013) with printed handouts to study test shape, chamber arrangement, and aperture type, examining foraminifer specimens under a stereoscope to study different test wall types and major differences between benthic and planktonic Foraminifera, and observing differences among assemblages of Foraminifera from different environments. For ostracods, students labeled SEM images with morphological features including the lateral outline, margins, and other internal and external features, and examined the morphological differences between ostracods found in different environments (assemblage exercise).

After completing these activities, students were asked to select a microfossil from an assemblage slide and use its morphological features to identify it to the genus (the genus identification exercise in the lab assignment was used for assessment) (Table 2). Students were given the option of either identifying a foraminifer or an ostracod and could choose the specimen they used for the activity from slides containing multiple specimens. Students were expected to identify the main morphological features of the microfossil (Foraminifera: shape, chamber arrangement, aperture type, wall type, benthic or planktonic; Ostracoda: lateral outline and valve margins [dorsal, ventral, anterior, posterior], size, and ornamentation). They used both print and digital resources provided to determine the genus; these resources included publications with images and descriptions of genera from the same regions as the specimens (Bergen & O'Neil, 1979; Stepanova, 2006) and resources that covered more taxa including Foraminifera.eu Guide to Benthic Species (Foraminifera Gallery, 2022) and An Illustrated Key to the Genera of the Foraminifera (Cushman, 1933). Students also had access to the morphological supplements they were asked to review prior to the laboratory session and their notes from previous portions of the laboratory assignment (See Supplement 2). Students were required to provide a labeled sketch of their specimen on paper and describe the process that they used to arrive at their identification. Students were encouraged to work in teams and asked questions of the teaching assistant or the instructor as needed. We scored this final genus identification exercise using rubrics to assess (a) how many of the expected identification steps they used (process completeness; Table 4), (b) the proportion of morphological features they correctly identified on their specimen (morphological accuracy; Table 5), and (c) the correctness of their genus identification (Table 6). The two graders were the primary instructor of the class and a researcher on this project. The two graders graded Foraminifera and Ostracoda questions independently, with the instructor of the class grading Foraminifera questions and a researcher grading Ostracoda responses by using the same rubric (Tables 4–6). We established the criteria for rating Foraminifera and Ostracoda responses in the same way. To achieve high interrater reliability, the graders iteratively revised the rubrics through discussion to ensure consistency between graders and scored all assignments using the same final rubric before data analysis.

In 2021, due to COVID-19, laboratory sessions with the teaching assistant were shortened to accommodate social distancing, with only half of the in-person students in a given section present for the first hour of the lab, then remote students would attend on Zoom, then the second half of in-person students would come to the third hour of the laboratory session (Table 1). To shorten the laboratory activity, content on the internal features of Ostracoda, using assemblages to infer depositional environments, and other microfossil groups were removed from the activities needing physical samples. Students were also given a word bank on the laboratory assignment containing the appropriate terms to use for each character. Whereas the in-person students used the same models and specimens in 2020 and 2022 for the genus identification exercise in the lab assignment that was used for assessment, remote students in 2021 and 2022 examined images of similar specimens online as well as 3D digital models of specimens in place of the models used in-person. For the in-person genus identification exercise, students were assigned a slide with ostracods or a slide with foraminifers but could choose among the specimens in 2020 and 2022. Remote students in 2021 and 2022 were assigned an image to identify based on the first letter of their last name. All students in 2021 and 2022 turned in their assignments digitally through the Learning Management System regardless of whether they did the in-person or the remote version of the lab. We scored this genus identification exercise in the same way as for the control and test groups using rubrics (Tables 4–6).

In 2022, laboratory instruction was designed to be primarily in-person and to fill the full 3-h session with a remote version available on request (Table 1). Students were asked to do the FossilSketch activities during the session instead of before. Assemblage exercises that were removed in 2021 were integrated into FossilSketch, allowing students to practice using Ostracoda and Foraminifera to enter the environments of deposition without physical specimens. One laboratory session (21 students) was completed primarily in person; however, the second laboratory session (22 students) was completed remotely due to a winter storm-related closure of the campus (Table 1). Students were assigned specimens for the genus identification exercises in the lab assignment as in 2021, and it was scored in the same manner as in 2020 and 2021 (Tables 4–6).

In all three years, the laboratory practical quiz was delivered digitally in the Learning Management System and included all taxonomic groups covered throughout the year. For this study, we assessed two open-ended questions, one for Ostracoda and one for Foraminifera (Table 2). Each question contained an image of the focal microfossil and asked students to describe the process you would use to identify this fossil to its genus. We scored their responses according to the "process" rubric used for the genus identification exercise (Table 4).

Analysis of genus identification assessments

To test whether students who used FossilSketch (test group, implementation years 2021 and 2022 combined) achieved higher scores on the genus identification exercise in the lab assignment and lab practical quiz than those that did not use FossilSketch (control group, year 2020), we compared median rubric scores between the test group and the control group

Table 4. Rubric for weighted scores for lab assignment and lab practical: Identification steps.

Identification of steps	No attempt	No evidence	Underachieved	Partially achieved	Fully achieved
Ostracoda (4)	0%	25%	50%	75%	100%
1. Right and left using length					
2. Outline					
3. Size	No attempt OR provided no steps	Described only one step	Described two steps	Described three steps	Described all four steps
4. Ornamentation					
Foraminifera (4)					
1. Test wall type					
2. Test Shape					
3. Chamber arrangement					
4. Aperture type					

Table 5. Rubric for weighted scores for lab assignment and lab practical: Correct elements identified.

Criteria (how many elements were identified)	% from total possible
Ostracoda (4)	0, 25, 50, 75, 100
Right and left using length	
Outline	
Size	
Ornamentation	
Foraminifera (5)	0, 20, 40, 60, 80, 100
Test wall type	
Test Shape	
Chamber arrangement	
Aperture type	
Benthic or planktonic	

Table 6. Rubric for weighted scores for lab assignment and lab practical: Genus ID.

Criteria	Incorrect	Similar	Correct
	0%	50%	100%
Correct identification of the genus	Didn't identify OR provided the wrong genus information	Identified a similar genus	Correctly identified the genus

Table 7. Engagement survey.

Reflection from learning
Q1: Did you go above and beyond the class requirements with regard to paleontology? If so, please explain what you did.
Q2: Did you work on the micropaleontology activities outside of class (other than class time)? If so, please explain what you did.
Q3: Do you think the micropaleontology activities in this class are and will be useful to you? How so?
Challenges and how they were mitigated
Q1: What did you dislike about micropaleontology activities in this class?
Q2: When did you feel uncertain or unsure about something while working on micropaleontology activities in this class? How did you deal with this uncertainty?
Q3: When were things difficult? How did you address the difficulty? Did you ask somebody for help? Were you able to find help?

using a Mann-Whitney U-test and an alpha value of 0.05. We compared each rubric element: identification procedure (Table 4), morphological accuracy (Table 5), and correctness of identification (Table 5) independently and as a composite weighted score, calculated as 40% of identification procedure, 40% morphological accuracy, and 20% of correctness of the genus identification (ID). We assigned the weights based on the relative importance of the three components, where identifying microfossils' characteristic morphological features and using the correct steps for genus identification are most important, while the final genus ID is less important. Mann-Whitney U-tests were performed using the function wilcox.test in the stats package of R programming language (R Core Team, 2013; Mann & Whitney, 1947; Wilcoxon, 1945).

Analysis of survey and focus group data

The engagement survey included questions that could be sorted into two categories: 1) reflections from learning and 2) challenges and mitigation strategies used (Table 7). All questions were open-ended. We used descriptive analysis based on coding to analyze these data. Responses in the reflection from learning category were coded as "yes," "no," "maybe," or "other." Student narratives in the challenges and how they were mitigated category were coded based on a general understanding of emerging themes, resulting in seven different codes for Question 1, six for Question 2, and nine codes for Question 3. Detailed information on codes and quotes associated with them are in Table S2.

We used a Chi-squared test to evaluate the independence of the most frequent codes for the engagement survey and group membership (control group or test group). For the Chi-squared test we combined the 2021 and 2022 counts as test group counts.

Focus groups were done with students in the control group (2020) and in the 2022 test group (See Supplement 1). Students who consented to participate were invited to provide feedback and comments in an open discussion during the laboratory session in each of the sections. In the control group they were asked about their experiences learning micropaleontology in the class, their challenges, and what they found helpful while learning micropaleontology. In the test group, students discussed what they liked and disliked about learning micropaleontology using FossilSketch, which activities they liked the most, and what changes to software they thought would be beneficial (See Supplement 1). Focus group data were coded based on a general understanding of emerging themes. For focus group data we used open coding to describe and categorize the transcribed data.

Results

Our results are based on data analysis of classroom assessments and survey data collected in the undergraduate paleontology course for geology majors.

Student performance data

Students who used FossilSketch scored significantly higher on the laboratory assignment on the correctness of the genus identification of Ostracoda (M-W $U = 38$, $p = 0.02$), on the ability to characterize morphological elements in Foraminifera (M-W $U = 40$, $p = 0.001$), and on the completeness of the identification process description for both Ostracoda and Foraminifera (M-W $U = 55.5$, $p = 0.013$ and M-W $U = 321.5$ $p = 0.008$, respectively) than the group that did not use FossilSketch (Figure 8, Table 8). Weighted laboratory assignment scores were also significantly higher in the test group than the control group for both Ostracoda (M-W $U = 38$, $p = 0.002$) and Foraminifera (M-W $U = 303.5$, $p = 0.006$; Figure 9, Table 8). Additional data on mean scores and standard deviations are presented in Table 8. Given students were not required to do both Ostracoda (control group $n = 10$, test group $n = 23$) and Foraminifera (control group $n = 34$, test group $n = 30$), the number of students assessed on the laboratory assignment were different between the taxa (Table S1).

At the end of the term, all students took the laboratory practical quiz, which asked students to provide a description of the identification process. Students who used FossilSketch ($n = 57$) provided more complete process descriptions than the control group ($n = 49$) for both Ostracoda identification

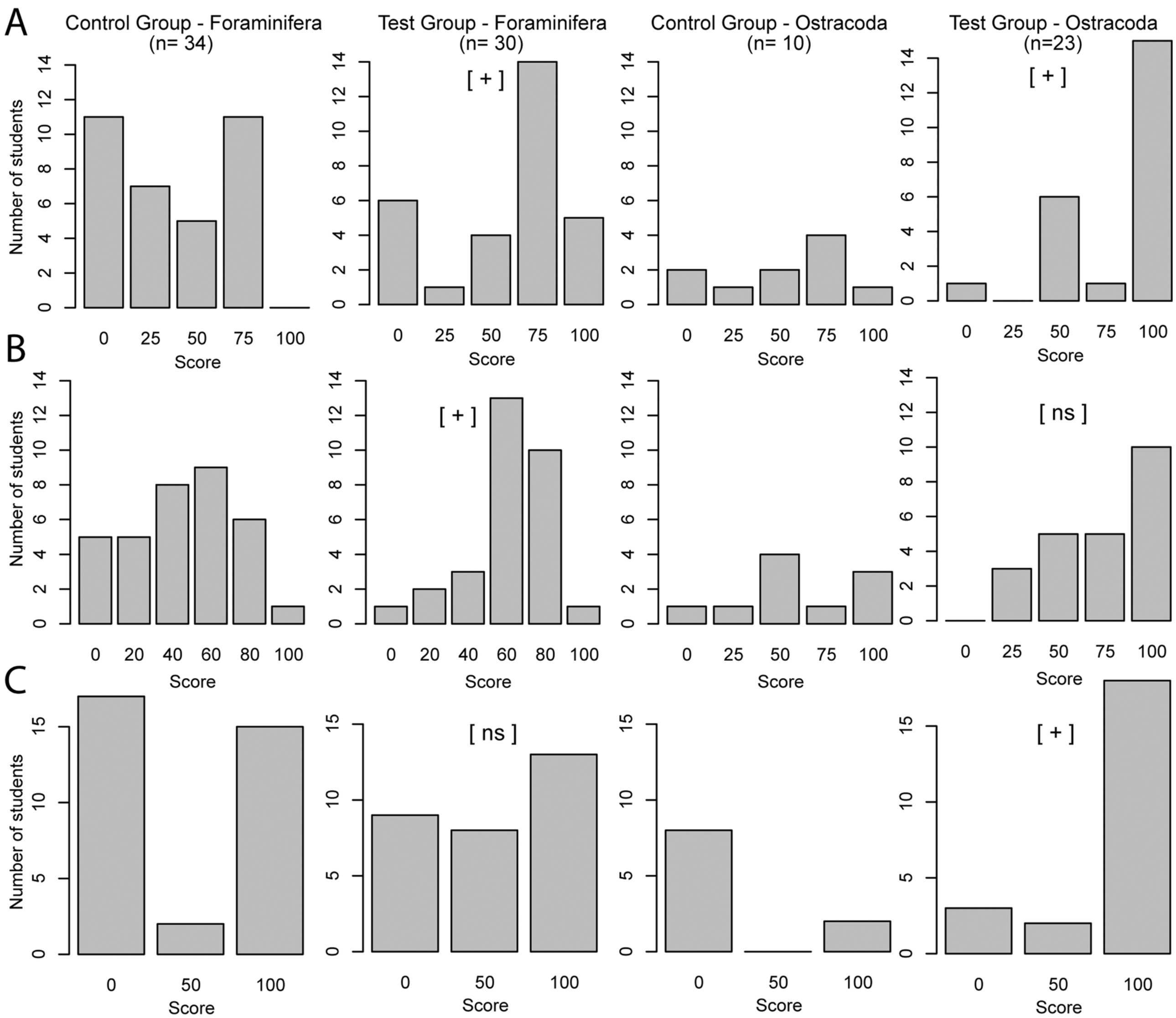

Figure 8. Laboratory assignment scores by rubrics: (A) identification process; (B) morphological accuracy or number of correctly identified elements; and (C) correctness of the genus identification. In test group panels, Mann-Whitney test results are indicated as follows: [+] = test group scored significantly higher, [ns] = no significant difference in scores. In no comparison did the test group score significantly lower.

Table 8. Comparison of rubric scores between control and test groups for the laboratory assignment and laboratory practical.

	Laboratory Assignment				Laboratory Practical
Type of microfossil	Process	Elements	Identification	Weighted Score	Process
Foraminifera	$U=321.5$ ($p=0.008$)*	$U=334.5$ ($p=0.015$)*	$U=455$ ($p=0.425$)	$U=303.5$ ($p=0.006$)*	$U=1042.5$ ($p=0.020$)*
Median (IQR) control	25 (0-75)	40 (20-60)	25 (0-100)	40 (30-61)	75 (25-93.75)
Median (IQR) intervention	75 (50-75)	60 (60-80)	50 (0-100)	63 (49-74)	75 (50-100)
Ostracoda	$U=55.5$ ($p=0.013$)*	$U=88$ ($p=0.277$)	$U=40$ ($p=0.001$)*	$U=38$ ($p=0.002$)*	$U=953.5$ ($p=0.004$)*
Median (IQR) control	62.5 (31.25-75)	50 (50-93.75)	0 (0-0)	50 (43.5-67.5)	50 (0-75)
Median (IQR) intervention	100 (50-100)	75 (50-100)	100 (100-100)	80 (70-100)	75 (50-75)

Mann-Whitney U test statistic is given with p-value in parentheses for Foraminifera and Ostracoda questions separately. Median and interquartile range (IQR) values are provided. For the number of students included in each group, see Table S1. *indicate significant differences ($p<0.05$).

(M-W $U=953.5$, $p=0.004$) and Foraminifera identification (M-W $U=1042.5$, $p=0.020$; Figure 10, Table 8).

Students' perspective on use of FossilSketch, survey and focus group data

The engagement survey included two categories of questions: 1) reflection from learning and 2) challenges and how students mitigated them. The results for the *reflection from learning* category showed that the percentage of students who self-described going "above and beyond" the class requirements with regard to paleontology increased from control to test groups, from 20% in 2020 to 30% and 35% in 2021 and 2022 (Figure 11). However, based on the Chi-squared test we cannot reject the hypothesis that the frequency of students who stated they went above and beyond is independent of the group (X^2=0.5577; p = 0.5). A typical quote from 2021 in response to whether the student felt they went "above and beyond" was: "Yes, by reading the assignments and taking in-depth notes and reaching to outside sources for any other information I did not understand."; and for 2022: "Yes I did. I researched fossils on my own that interested me as well as completing everything to the best of my ability" (for all survey responses coding and students' quotes, see Tables 9, Table S2).

The percent of students who worked on micropaleontology activities outside of class increased from 44% in the control group to 62% in 2021 and 53% in 2022 (Figure 11). However, based on the Chi-squared test we cannot reject the hypothesis that the frequency of students who stated they worked on activities outside of class is independent of the group (X^2= 1.2243; p = 0.27). A consistent theme from the control group is represented in the following quote: "Yes, I went to office hours to work on labs and ask the TA questions." In 2021 students provided more detailed responses, and many indicated they did not finish the lab in the class and used FossilSketch to finish at home. Examples of what several reported include: "Yes, I mostly did the lab outside of class because I don't like to rush it all in one hour. I spent a couple of hours trying to fit my mystery ostracod into a genus listed in the paper, played FossilSketch for maybe an hour or two, and finished the lab." Students who worked remotely in 2022 said: "Yes, my lab was during the time of the freeze so I did the remote option."

Most of the students in the test group reported that micropaleontology will be useful to students in the future, with 87% in 2021 and 62% in 2022 in the test group compared to 40% in the control group in 2020 (Figure 11). The responses to open-ended comments in 2020 include yes and no responses for the usefulness of micropaleontology knowledge in the future. For students who responded negatively, the following quote best captures their experiences: "I don't think so. I want to do environmental consulting so I'm not sure how this will benefit me." However, in 2021 there were no students who said that micropaleontology will not be useful, a typical quote from 2021 pointed to multiple applications of micropaleontology: "Yes. It would be useful to know about the occurrences of different types of microorganisms for all sorts of purposes, such as depositional environment interpretation, biostratigraphy, and climate change studies." Similarly, in 2022, students pointed to various applications of micropaleontology: "Yes, because it will give me a better wholistic (sic) understanding of geology." Based on the Chi-squared test we found that the frequency of students who stated that micropaleontology is useful to them was dependent on group membership (X^2 = 11.2; p = 0.0008), with the test group giving this response more often.

The second category of questions focused on challenges and how students mitigated them. The first question was:

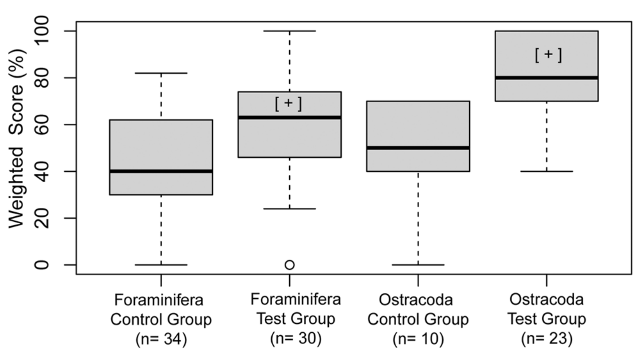

Figure 9. Weighted scores for the laboratory assignment. The bold line is the median, the box extends to the interquartile range, and whiskers are 1.5 times the interquartile range.

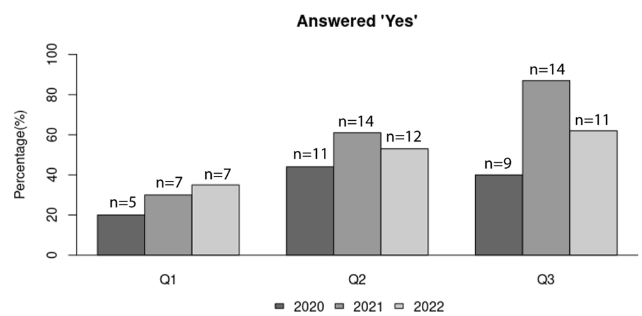

Figure 11. Engagement survey results: Reflection from learning. Q1: Did you go above and beyond the class requirements with regard to paleontology? Q2: Did you work on the micropaleontology activities outside of class (other than class time)? Q3: Do you think the micropaleontology activities in this class are and will be useful to you? n indicates a number of responses.

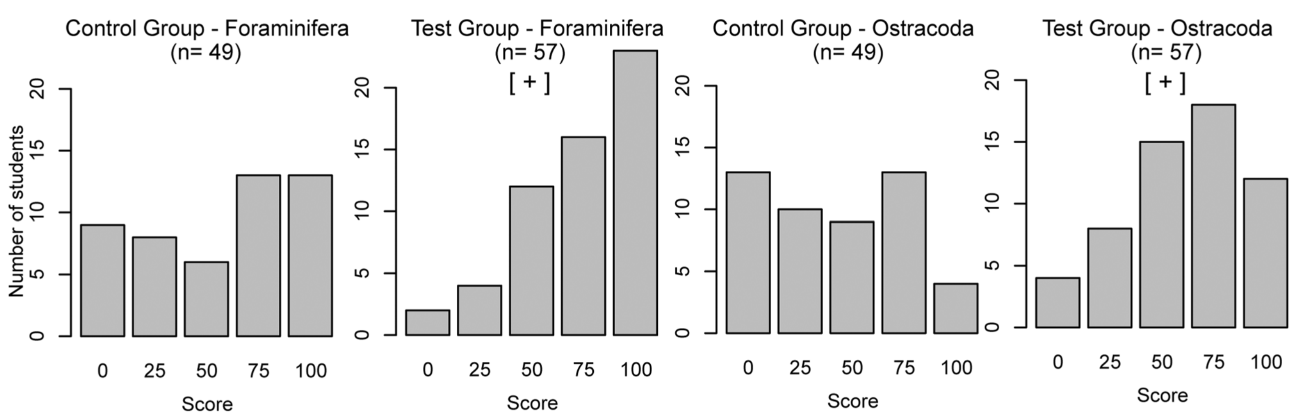

Figure 10. Laboratory practical quiz scores. The scoring method is identical to the process score for the laboratory assignment.

Table 9. Qualitative coding for survey questions on reflection from learning.

Survey question	Codes	Example quotes
Q1: Did you go above and beyond the class requirements with regard to paleontology? If so, please explain what you did	yes	"Yes, I put in extra hours trying to understand the material"
	no	"Nope, the class and concepts are very new to me"
	maybe	"I'm not sure if I went above and beyond in this class yet, but i have met all requirements so far."
Q2: Did you work on the micropaleontology activities outside of class (other than class time)? If so, please explain what you did	yes	"yes, I work on the labs outside of class hours"
	no	no
Q3: Do you think the micropaleontology activities in this class are and will be useful to you? How so?	yes	"Yes, understanding past climates are important for understanding the future."
	no	"No, i plan on focusing in hydrogeology and found this had little help if none"

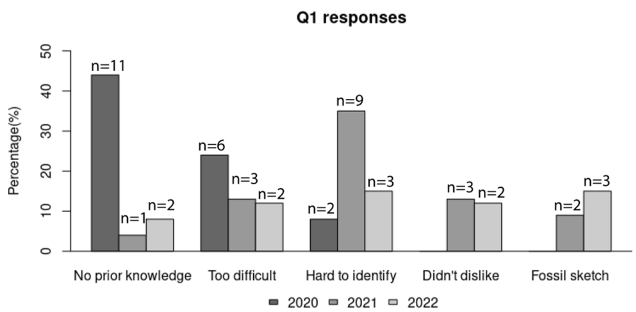

Figure 12. Engagement survey results: Challenges and how students mitigated them. Q1: What did you dislike about micropaleontology activities in this class? n indicates a number of responses.

What did you dislike about micropaleontology activities in this class? Students' responses fell into five main themes: they disliked having "no prior knowledge," micropaleontology is "too difficult," microfossils are "hard to identify," some "did not dislike anything," and some students disliked FossilSketch (Figure 12, Table 10).

Students' responses showed that about 54% of students in the control group disliked that they did not have enough prior knowledge, compared to less than 10% of students in the test group (Figure 12). A typical response associated with this theme is: "I didn't like that we had no previous knowledge or any intro to help us understand what we should be looking at." The percentage of students who said that micropaleontology is too difficult was also highest in the control group, reaching 23%, and dropping to less than 15% in test years. Students in the control group said: "There is so much material taught in a small time frame that I struggle to understand what just happened before we go to a completely different topic." We observed the highest number of students who said that microfossils are hard to identify in 2021, with the following example of a quote: "I dislike how nit-picky micropaleontology can feel sometimes. Mostly in the sense of taxonomic classification. It seems like there is (sic) so many types of organisms and sub-types, but to me, they are basically the same." Two other themes: "did not dislike anything" (12-14%), and "disliked FossilSketch" (8-15%), only occur in test years (Figure 12, Table 10, Table S2).

The second question was: When did you feel uncertain or unsure about something while working on micropaleontology activities in this class? How did you deal with this uncertainty? Students' responses were grouped into five main

Table 10. Qualitative coding for survey questions on challenges and how students mitigated them.

Survey question	codes	quotes
Q1: What did you dislike about micropaleontology activities in this class?	no prior knowledge, no guidance	"I didnt like that we had no previous knowledge or any intro to help us understand what we should be looking at"
	micropaleontology is too difficult, tedious	"The fact that I was lost initially "; "it was tedious"
	not useful	"They seem useful only if thats what you plan on doing but otherwise not helpful"
	microfossils are hard to identify	"Some of the microfossils were hard to see and identify "
	disliked FossilSketch	"I disliked the fossil sketch activity."
Q2: When did you feel uncertain or unsure about something while working on micropaleontology activities in this class? How did you deal with this uncertainty?	asked TA	"I felt uncertainty when describing the microfossils, I looked at handouts and asked the TA for help"
	searched online	"Uncertainty is usually in lab and google is the answer to most problems these days"
	asked questions	"Mostly during lab and I overcame this by asking questions and getting help"
	self-study	"Every lab right at the beginning. I just keep reading"
	used FossilSketch to practice	"Yes, I just repeated the modules until I felt comfortable with my knowledge about identification"
Q3: When were things difficult? How did you address the difficulty? Did you ask somebody for help? Were you able to find help?	asked TA	"I asked my peers and the TA for help"
	searched online	"Most help came from google and fellow class mates"
	asked questions	"again from the start, I ask fellow classmates for their knowledge and we were all confused"
	self-study	"The lab was kind of difficult but I really looked at the supplemental materials and lectures to help."
	apertures were hard	"The lab resources helped me figure out most of my problems with the lab. Aperture was my greatest difficulty and using fossil sketch did not help that."
	FossilSketch bugs	"Working with fossil sketch was difficult because of the many bugs and errors I encountered. Switching browsers and computers did little to help."
	difficult but managed to figure out	"Difficult with some of the specific questions in lab, tried to research more, did not ask for help but should have, mostly found answers"
	asked questions	"I asked for help from my lab partners, they helped me think through stuff"

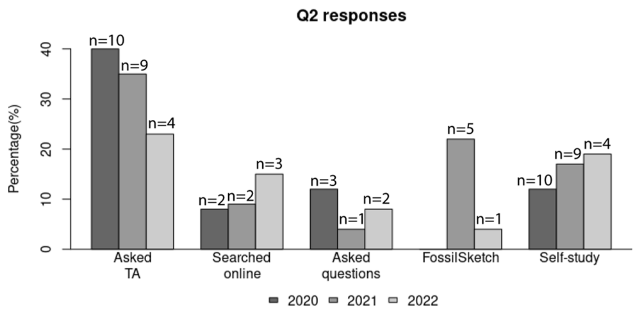

Figure 13. Engagement survey results: Challenges and how students mitigated them. Q2: When did you feel uncertain or unsure about something while working on micropaleontology activities in this class? How did you deal with this uncertainty? n indicates a number of responses.

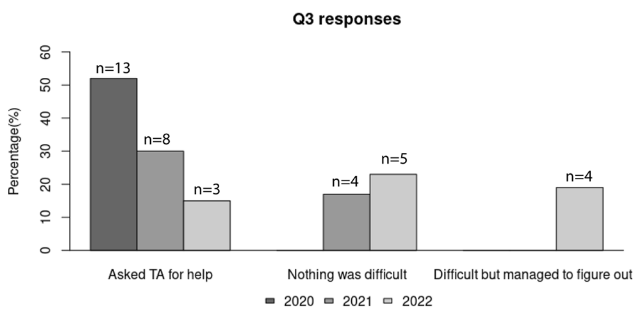

Figure 14. Engagement survey results: Challenges and how students mitigated them. Q3: When were things difficult? How did you address the difficulty? Did you ask somebody for help? Were you able to find help? n indicates a number of responses.

themes: that students dealt with uncertainty by "asking a TA," "googling or looking online," "asking questions," "using FossilSketch to practice," and "self-study" (Figure 13, Table 10).

Students' responses suggest that they may have needed less TA help in test years; in 2022 only 22% of students needed the TA's help compared to 40% in 2020 (Figure 13). A typical response for 2020 was: "I feel fairly uncertain for most activities. I deal with this by having the TA explain it to me which helps a lot." The number of students who said that they used google or searched online slightly increased from 8% to 15% from control to test years. A typical student response associated with the control group in 2020 was: "Most of the lab and class I have felt uncertain and unsure because almost everything is new. Working to understand by asking questions and reading materials." Students in 2021 and 2022 said that they used FossilSketch to practice. They said: "Yes, I just repeated the modules until I felt comfortable with my knowledge about identification." The number of students who dealt with uncertainty by reading and studying independently increased slightly from 14% to 19% from control to test years. A typical quote for 2022 is: "Sometimes I got some morphologies mixed up and I will try to fix this with more studying."

The third question was: When were things difficult? How did you address the difficulty? Did you ask somebody for help? Were you able to find help? A total of seven codes were identified for these questions, of which we selected three themes as representative of change linked to FossilSketch use: that students addressed the difficulty by "asking TA for help," that "nothing in fact was difficult," and that "things were difficult, but students managed to overcome the difficulty" (Figure 14).

Similar to the previous question, the percent of students who needed help from a TA decreased from 52% to 15% from control to test years. It is noteworthy that only in test years did students say that nothing was difficult, and in 2022 only 18% of students said that things were difficult, but they managed on their own. The following quote is a good example associated with this particular theme in 2022: "Things were difficult when I first sat down to work on the activity, but then I looked up words that I was unsure of and I was able to figure it out".

Focus groups revealed main themes for control and test groups. In the control group, students said that they were often confused, described microfossils as hard to identify, and said that they needed guidance through activities. Students pointed to their lack of prior knowledge. They concluded that they needed more lectures before the lab. Students noted that sketching microfossils is very helpful for learning about their morphology. They also said that the lab environment can constrain and limit the learning experience, such as when the microscopes are not very high quality and do not allow them to see the microfossils clearly.

The focus group for students in 2022 revealed that students overall enjoyed FossilSketch but pointed out multiple software bugs. They also wanted FossilSketch to provide them with even more feedback. Among the different FossilSketch activities, students said that the genus identification activity was their favorite, because they could draw and go through identification step by step: "I like the section right before the fossil assemblage. If I was working with this lab, it really worked with supplementing it. I like that you could draw it, and it was really clear. That was great." "I felt that it was easy to remember some of the different qualities, features in like ostracods. I felt it was easier for me to remember everything while going through." "I felt that ostracod sections were really good, in like it was really nice to interact with it and be able to draw the shape and things like that." Students who had to work on the micropaleontology lab remotely due to the ice storm in 2022 or could not finish during the class time appreciated being able to do lab remotely using FossilSketch: "Since we were completely online for this lab, it was nice having FossilSketch, so we could see and interact with fossils online."

Discussion

Students' performance data come from the two types of classroom assessments: the genus identification assignment and laboratory practical quiz. These data showed that students who used the interactive software FossilSketch were better able to understand the process of microfossil identification, recognize morphological characteristics, and achieve a correct identification than those who did not use FossilSketch. For Foraminifera, however, genus identification was not significantly greater in the test group, indicating that students in the control group could arrive at the correct genus identification even though they had less understanding of the process and morphological characteristics. This implies that in the control group, students mainly based their identifications on picture matching with the reference guides whereas students in the test group used evidence-based practices to achieve a correct identification. In contrast, students in the control group were equally able to recognize morphological features in Ostracoda, but their ability to identify genera and describe the identification process improved significantly. This can be explained by ostracods having relatively fewer morphological elements to distinguish between than foraminifers. Overall, these results show that FossilSketch improves students' understanding of the identification process compared to traditional methods. Thus, classroom use of FossilSketch can facilitate broader training of future micropaleontologists for growing geoscience fields in climatology, environmental protection, and energy.

Using FossilSketch resulted in improved performance in our study. Similarly, data on another educational software tool, Mechanix, also developed in the Sketch Recognition Lab at Texas A&M University for homework problems in mechanical engineering, showed that in controlled studies, people who used Mechanix tended to have greater pre- to post-test score improvement (Brooks et al., 2017). A meta-analysis of 50 controlled evaluations of intelligent computer tutoring systems also showed that the improvement in performance was significant in 39 of them (Kulik & Fletcher, 2016). There is little data on long-term retention for users of intelligent tutoring systems. However, data on FossilSketch showed that the effects of using FossilSketch persists throughout the semester, and students who used FossilSketch were able to better explain the process of identification two months after the laboratory experience than the students who did not use FossilSketch.

We also found that students who used FossilSkech reported working outside of class more than the control group, although these differences between the control and test groups were not statistically significant. The tendency to work outside of class during test years was probably partially driven by the necessity of remote learning during the COVID-19 pandemic in those years. We cannot estimate if the time spent learning between the control and test years was different. It is possible that in test years students spent more time learning through FossilSketch. However, FossilSketch enabled students to actively engage with micropaleontology laboratory activities remotely, which would not have been possible when the laboratory assignment was centered on physical specimens alone. Based on students' survey responses, FossilSketch allowed them to deepen their practice at home.

Students using FossilSketch became more aware of applied micropaleontology in research and industry, as evinced by their belief that micropaleontology knowledge will be useful for them in the future even though they received the same lecture content as students who did not use FossilSketch. The educational video on applications of micropaleontology and assemblage exercises (Belanger et al., 2020b) emphasizing the importance of microfossils for paleoenvironmental reconstructions increased student engagement with the analysis of micropaleontological data and made students more aware of the applications of microfossil research. In other studies, participants in experiential learning activities improved their discipline-specific knowledge and skills that allowed them to learn about broader research-related career paths and improve retention (Rodenbusch et al., 2016; Judge et al., 2022). In the present study, we observed statistically significant changes in the number of students who said that micropaleontology is useful for them.

Students who used FossilSketch also felt they were better prepared for the micropaleontology laboratory assignment or genus identification exercise. Significantly fewer students reported that they lacked prior knowledge in FossilSketch-based classes and that they needed TA help. In addition, fewer students in the test groups reported feeling that the micropaleontology laboratory activities were "too difficult." Some students in the FossilSketch-based classes reported that they did not find anything difficult, or if they did, they were able to find answers and overcome any difficulty. Thus, FossilSketch successfully promoted independent work by providing feedback and support to students for independent study. Other educational software tools, such as Mechanix and SketchTivity, which were also developed in the Sketch Recognition Lab, helped students in understanding the problems, and the majority of students reported that they would prefer the software approach over pencil and paper (Hurt et al., 2020; Runyon et al., 2021; Williford et al., 2016). In our study, students in test years reported that they were able to find answers, and, even when tasks were challenging, they studied and read to deal with uncertainty. This suggests that FossilSketch may have contributed to making them more independent learners.

Unique to test years, multiple students stated that they did not dislike anything about the microfossil activities. Focus group feedback from students was also positive, and they found that using FossilSketch in the classroom was enjoyable and useful. During the focus groups, students who learned microfossil identification with the aid of FossilSketch also expressed less confusion about the process of identification. Some students mentioned that the genus identification exercises were their favorite activities because they could sketch and follow step-by-step instructions in FossilSketch. Other researchers found that sketching benefits learning across a wide range of disciplines, including geosciences and biology (Forbus et al., 2011, 2017; Quillin & Thomas, 2015). We infer that playing mini-games allowed students to achieve a higher success rate with microfossil identification, which is supported by the higher Ostracod genus identification scores, and higher lab assignment weighted scores for both Foraminifera and Ostracoda.

Although overall feedback from students who used FossilSketch was positive, some students said they did not like FossilSketch itself. Their dislike pointed to software bugs and indicated that FossilSketch did not provide sufficient feedback during the activities in 2021. Students did not mention this in 2022, when feedback from FossilSketch was added to most of the activities (Table 1). Students in the test group also more frequently reported feeling that microfossil identification was difficult than the control group, although the test group performed significantly better on the classroom assessments. In another study, researchers using a randomized experimental approach and identical course materials found that students in the active classroom learn more, but they feel like they learn less. They associated this negative correlation with the increased cognitive effort required during active learning (Deslauriers et al., 2019). Similarly, in our study we see evidence that students learned more when they engaged with FossilSketch, and their feedback indicated that they had to work harder.

Learning conditions were different between years due to the COVID pandemic, with 2021 and 2022 being more unfavorable due to pandemic and winter storm conditions that limited contact time with the TAs and instructors and the more limited TA expertise (Table 1). Despite these challenges, and limited TAs' availability during the test years, students scored higher on classroom assessments than in the control year. This suggests that the use of interactive software, such as FossilSketch, can help students overcome the learning difficulties present in the test years as well as the challenges presented by instructional disruptions. Furthermore, this demonstrates that novice TAs are able to instruct using FossilSketch and provide a learning experience superior to expert TAs without the software. This suggests that FossilSketch could be a deployable teaching and learning tool in undergraduate classrooms for instructors without micropaleontological expertise and can even enhance instruction by experts. FossilSketch also allowed instructors and TAs to use it in teaching micropaleontology lab remotely, and, based on students' feedback, they appreciated that they could effectively engage in learning away from the classroom laboratory.

Limitations

The results of this study should be viewed with certain limitations. First, the sample size of the study is relatively small, which makes the results less generalizable (Table 2). Additionally, due to an insufficient population size, we could not compare learning gains by race/ethnicity, gender, or other factors. Therefore, it is unknown whether the use of FossilSketch benefited students evenly, or if some demographic categories experienced larger benefits than others. Second, the COVID-19 pandemic and accommodations that were provided to students as a result of it may have impacted the results. In 2020, students attended lectures and completed the laboratory assignment before the onset of the pandemic, but the laboratory practical quiz was administered when all students were fully remote. In the subsequent years 2021 and 2022, students were better adjusted and familiar with remote learning which may have affected the results (Table 1). Third, when students used FossilSketch, they were instructed to watch instructional videos and go through mini-games and exercises independently, but some of the students may not have followed these instructions despite reporting to the instructor that they completed the task. If some students did not complete the FossilSketch activities, they may have been unprepared to identify microfossils. However, usage data collected by the software suggests that the vast majority of students did use FossilSketch, and our data indicate that students who had FossilSketch available to them did score higher on microfossil identifications. Our usage data only provides information on completed assignments, but not on the time spent in FossilSketch. Thus, we cannot estimate if the time spent learning between the control and test years was different.

Implications

FossilSketch increased student learning of fossil identification through a scaffolded learning experience and provided real-time feedback to students learning outside of the classroom. Students who used FossilSketch were better able to identify microfossils and explain the process of identification of classroom assessments, which implies that this scaffolding improved student learning. Students in the control group were often overwhelmed with the task of identification, but students using FossilSketch were able to learn the morphology through gamification and practice using discrete mini-game tasks. Students also pointed out that they enjoyed sketching the microfossils and doing the step-by-step identification exercises, suggesting that having a well-defined process for identification made them more comfortable with the task. Students appreciated the automatic feedback and proposed adding even more features to increase the amount of feedback. We recommend that instructors teaching taxonomic identification in paleontology and organismal biology courses introduce students to stepwise process for taxonomic identification and reinforce that process through the design of the laboratory exercises.

In general, students were excited to use FossilSketch, but in the initial implementation multiple students requested that FossilSketch contain additional feedback features. After including automated feedback, students were more satisfied with the learning experience and did not request additional feedback from FossilSketch or from the TAs. This demonstrates the importance that students place on real-time feedback as they work, and that students are comfortable with feedback from software substituting for feedback from in-person instructors. Expansion of FossilSketch, or the development of similar software for other taxonomic groups, would allow students to receive this feedback remotely and practice identification skills independently, relieving some of the logistical challenges of studying for specimen-based laboratory courses that characterize much of paleontology and organismal biology curricula. We recommend that geoscience programs emphasize the integration of digital interactive instructional activities across the curriculum to allow students the flexibility to develop and practice skills independently outside of the formal class activities.

FossilSketch can be used in all levels of undergraduate and graduate courses, and instructors can modify the modules they use to be appropriate for their course. FossilSketch is customizable by the instructor to be appropriate for an upper-level undergraduate paleontology course, lower-level undergraduate Earth history course, or a non-majors course in Earth systems or environmental science. It can also be used to support training undergraduate and graduate students doing research with Foraminifera or Ostracoda. Students should watch the informational videos embedded in FossilSketch prior to beginning the exercise in the classroom or laboratory session. It is helpful if they already understand basic taxonomic concepts and are aware that fossils and sedimentary records can be used to reconstruct past environments. Suggested lesson plans for lower-division undergraduate general Earth science courses and upper-division Earth science major courses can be found on the Teach the Earth website (Belanger & Stepanova, 2023). The video lessons and integrated feedback allow students to have a guided learning experience about microfossils even if the instructor does not have prior experience teaching with microfossils. For upper-division paleontology courses, where students are expected to learn taxonomic identification, like in the course tested here, we suggest using FossilSketch early in the semester so students gain familiarity with the identification process and can apply that skill to other organisms. In lower-division Earth science courses, we recommend using FossilSketch toward the end of the course and focusing on the modules that emphasize overall morphology and the application of assemblages to ecological and environmental questions. This later use of FossilSketch will allow the lower-division students to synthesize information they learned earlier in the course as they apply fossil identification to paleoenvironmental reconstruction. In our study students in the upper-division paleontology course spent up to 3 h learning, and students in the lower-division Earth science courses (our unpublished data) spent up to 2 h learning.

Conclusion

Based on the data we collected with geology-major junior and senior undergraduate participants, including both students' performance measures and survey and focus group analysis, FossilSketch was a successful tool to achieve our learning outcome goals: (1) to increase student comprehension and retention of micropaleontology knowledge, and (2) to increase student engagement with analysis and application of micropaleontological data. Classroom evaluation showed that using FossilSketch resulted in improved classroom assessment scores, with students reporting being more successful at independent learning, and feeling better prepared for micropaleontology lab.

FossilSketch is the first software that uses sketch recognition and allows for remote teaching of a traditionally only lab-based subject, micropaleontology, and, because of built-in feedback, it allows non-expert instructors to effectively teach micropaleontology. FossilSketch enabled students to actively engage with micropaleontology laboratory activities remotely and to deepen their practice at home.

Future work

Our future work on FossilSketch project encompasses making it a self-sustainable software for general use in various science courses. We will work on advancing the features and capabilities of FossilSketch by developing an instructor dashboard to help them create, share, and customize classroom activities, and improving the existing student dashboard to provide more autonomy to users.

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Authors' contributions

Dr. Anna Stepanova performed data collection, qualitative data analysis, and wrote the manuscript. Dr. Christina Belanger contributed to data analysis, performed quantitative data analysis, interpretation, and writing and revising of the manuscript. Dr. Saira Anwar contributed to research study concept and design and wrote the manuscript. Dr. Christine Stanley and Dr. Tracy Hammond contributed to data interpretation and editing of the manuscript. Dr. Josh Cherian was a PhD student and the main developer of FossilSketch software. Ankur Nath developed two mini-games and helped create the figures.

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ORCID

Anna Stepanova http://orcid.org/0000-0001-5927-6536
Christina Belanger http://orcid.org/0000-0002-1582-7647
Saira Anwar http://orcid.org/0000-0001-6947-3226
Christine Stanley http://orcid.org/0000-0002-8697-7220
Josh Cherian http://orcid.org/0000-0002-7749-2109
Tracy Hammond http://orcid.org/0000-0001-7272-0507

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