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A Remote View into the Classroom: Analyzing Teacher Use of Digitally Enhanced Educative Curriculum Materials in Support of Student Learning

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ABSTRACT

When integrated into online curriculum modules for students, educative curriculum materials (ECMs) can enhance teachers' enactment of these modules. This study investigated (1) the use of digitally enhanced ECMs built into an online plate tectonics curriculum module by teachers with different backgrounds and teaching experience, (2) the relationship between teachers' use of ECMs and student learning gains, and (3) teacher reflections on the value of the ECMs they used. We studied 26 teachers who taught middle and high school students ($n = 1,098$) by analyzing teacher log files automatically generated by the ECMs, teacher reflections collected with post-implementation surveys and interviews, student log files, and student learning gains from pretest to posttest. Results indicate that (1) there were large variations in the amounts and types of ECM features teachers accessed, (2) middle school teachers accessed significantly more ECM features than high school teachers $p < .01$, (3) students of teachers who used ECMs during class time made significantly higher learning gains than students of teachers who used them only before and/or between class time, $p < .05$, and (4) teachers most valued ECM features on student assessment. An overall non-significant, but positive, correlation between the total teacher interactions with ECMs and student learning gains was observed, $r = 0.20$, $p = .32$.

KEYWORDS

Educative curriculum materials; log analysis; plate tectonics; remote data collection; teacher training

Introduction

Research on educative curriculum materials (ECMs) designed to support teachers is growing. ECMs are teacher training materials situated in the same curriculum materials used by students. Ball and Cohen (1996) outlined multiple factors to consider when developing ECMs to enact curriculum-based reform in the classroom, including students' prior knowledge, teachers' content understanding, available materials, classroom environment, and support of the broader community. Since then, researchers have crafted design guidelines (Davis & Krajcik, 2005) and heuristics (Davis et al., 2017) for developing ECMs for science teaching. Krajcik and Delen's (2017) review of six studies indicated that teachers can use ECMs to learn both new curricula and innovative science teaching practices. However, they concluded that much research needs to be done, particularly on what specific types of support teachers need, how much information to include, and how to scale up their use by more teachers.

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As more and more curriculum materials move online, delivering ECMs digitally becomes important. In 2019, slightly more than half of the science teachers in the U.S. used online materials daily in their classrooms (Gallup, 2019). According to a study by Winter et al. (2021) teachers' use of online materials for students soared during the COVID pandemic even though teachers were not trained in how to best use them (Hodges et al., 2020). In the coming years, experts project a surge in new online educational materials for students (Bradley, 2021) and the need for teacher training in both new technologies and pedagogical strategies (Schleicher, 2020; Wilichowski & Cobo, 2020, 2021). As a result, ECM development that supports teachers' use of online curriculum materials is an important consideration in transforming science teaching. ECMs paired with online curricula allow teachers to study new curriculum materials at their own pace and at a time convenient to them without the limitations and expenses typically associated with traveling to attend teacher workshops (Greenhow et al., 2009).

We developed digital ECMs to support teacher enactment of an online plate tectonics module for secondary school students (Lord, 2020; Pallant et al., 2022). In this study, we investigated the use of these ECMs by 26 middle and high school Earth science teachers based on computer-generated logs along with teacher post-implementation reflections from surveys and interviews. We also connect the patterns of ECM usage with student learning outcomes.

In this paper, we first review literature on ECMs. We describe the theoretical framework, curriculum context, and methods, including subjects, data sources, and analyses. We report results by research question and further discuss them in the context of enacting a new curriculum. Finally, we mention limitations as well as areas for further research.

Literature & background

Importance of teacher training

Teacher differences in pedagogical subject knowledge can explain variations in student learning outcomes associated with a newly implemented curriculum (Magnusson et al., 1999), and several studies have suggested a link between teacher training and student learning outcomes (Fishman et al., 2003; Lai & McNaughton, 2016; Meissel et al., 2016; Penuel et al., 2011). Researchers have found that teachers' subject matter knowledge is a strong predictor for student learning outcomes (Hill et al., 2005; Ma, 2010). Donna and Hick (2017) found that ECMs can be used effectively to help teachers develop subject matter knowledge needed to implement a new curriculum. ECMs must be robust in promoting teacher learning of not only the subject matter, but also how to teach it (Davis & Krajcik, 2005). When used in conjunction with well-designed curriculum materials, ECMs can fill the dual need that Penuel and Gallagher (2009) found for Earth science teachers; they need access to both in order to successfully implement new curriculum. Because plate tectonics is a complex science topic (McDonald et al., 2019), often taught at the middle school level by teachers who have limited geoscience education (O'Sullivan et al., 2003), supporting subject matter knowledge for teachers with different backgrounds and levels of understanding is essential. Finally, Earth Science is best taught through an inquiry-based approach (Chang & Mao, 1998) where teachers remain engaged (Kirschner et al., 2006) and actively facilitate inquiry-based lessons to maximize student learning (Furtak et al., 2012). As such, building teachers' pedagogical content knowledge on how to teach inquiry-based Earth science units is especially important.

The rise of digital ECMs

Research shows that if educative materials for teachers are integrated into the curriculum materials students use, teachers can more effectively learn how to teach with the curriculum (Arias et al., 2016, 2017; Ball & Cohen, 1996, 1999; Billman et al., 2014; Brown, 2011; Davis et al., 2017; Remillard, 2000; Schneider et al., 2000). While the study of digital ECMs is a relatively new field and "there has been little work on the intersection of digital media with educative curriculum" (Loper et al., 2014, p. 1118), there are a few studies that focus on digitally enhanced ECMs for science curriculum (Davis et al., 2004; Duncan et al., 2011; Loper et al., 2017, 2019). Davis et al. (2004) created a suite of online lesson plans to guide teacher implementation of hands-on elementary science lessons. The ECM design was based on the "Guidance on Demand Principle," which provides teachers with help as they need it (Davis et al., 2004; Shrader & Gomez, 1999). Embedded hints strategically placed at various points in online lesson plans allowed teachers to access educative features around science content and support students in a "just-in-time" manner. Loper et al. (2017) studied how teachers used online, multimedia ECMs (presented as videos) on supporting students' scientific argumentation skills as they prepared to teach hands-on classroom activities. They found that teachers were more likely to view videos that were embedded in the lesson plan rather than offered in a separate library. In addition, they found that teachers were more likely to watch videos at the beginning of a new lesson. Duncan et al. (2011) also embedded ECMs directly into online student lessons by placing text-based call-outs at the beginning of each lesson in a web-based science unit. Although 52% of teachers in the study said that the supports designated as "in-class tips" were very useful, no teachers used them during class. In fact, according to teacher self-reports, the ECMs that were explicitly designed to be used during class time were used only during preparation. This research suggests the importance of future study around the utility of different types of teacher tips and the timing of their use.

When considering digital technologies for learning, Neumann and Waight (2020) stated, "Digital technologies and ecologies have developed into complex, authentic learning opportunities that are no longer tools used in science education but have become means for science education" (p. 1526). The use of digital curriculum soared during the COVID pandemic and has shown no sign of slowing (Bradley, 2021). Past research has shown that to enact a new technology-based curriculum, teachers must have familiarity with and confidence in the new technology (Edelson, 2001), as well as an understanding of how the technology can support their teaching and improve student learning (Cviko et al., 2012; Inan & Lowther, 2010). With an increase in the use of digital curriculum, the need for digital ECMs to support teachers' use also increases. While ECMs should be thoughtfully designed by curriculum developers (Lord, 2020), their use and utility must be studied to inform future research (Lee et al., 2022).

Teacher ECM use and student learning

The shift to digital curricula and digital ECMs affords a shift to digital data collection. For years, researchers interested in educational data mining and analytics have looked at student log files to uncover details on how students use computer-based curriculum materials (Baker & Yacef, 2009; Gobert et al., 2013; Martin & Sherin, 2013). Recently, data mined from students' use of online materials have been used for many different purposes, from assessing student learning on interactive games (Horwitz et al., 2022) to training intelligent tutoring systems (Henderson et al., 2020) and giving students real-time feedback (Lee et al., 2021). In contrast, mining logs of teacher use of ECMs is a new field for exploration. We identified two studies that analyzed log files of teachers' use of the multimedia ECMs the authors developed (Loper et al., 2017, 2019). These studies analyzed log files generated while teachers viewed ECM videos in an online teacher guide to determine which videos were used, how often, and when. Like other researchers of traditional ECM studies (Arias et al., 2016; Billman et al., 2014; Schneider et al., 2000), Loper et al. (2019) found large variations in teachers' use of ECMs in terms of the timing and frequency of use, but did not attempt to correlate teacher use of ECMs with student gains. The question remains, does the amount of teacher access to digital ECMs, the type of ECM features they access, or the timing of use relate to student learning?

Unlike the majority of studies on ECMs, which are based on direct observations of teachers in classrooms or teacher-self reports, this novel study focuses on data generated by logs of teacher and student actions. By analyzing the digital traces that teachers leave behind when they interact with online ECMs, in concert with those left by students using the online curriculum, we can determine not only the amount of use of ECMs by teachers, but also the timing of their use. In this way, we can distinguish between time preparing prior to implementation and time during class adopting the strategies they learn from the ECMs (Sherin & Drake, 2009). Through fine-grained log data, we can also explore variation in the use of three unique ECM features developed for the plate tectonics module: teacher support tips, student support tips, and embedded tools. We investigate which features are used most often and by which teachers, if the teachers' use of these features correlates with student learning, and which features are most valued by teachers.

Theoretical framework for design and research of ECMs

Knowledge is constructed through interactions with people as well as with materials and tools reflecting the culture and norms of a community. As we designed digital ECMs to develop teachers' *knowledge* of how to enact a new curriculum with a pedagogical approach unfamiliar to them, and at their own pace on their own, we invoke distributed intelligence to ground this study. Pea (1993) noted that "the material distribution of intelligence originates in the situated invention of uses for aspects of the environment or the exploration of the affordances of design artifacts, either of which may contribute to supporting the achievement of an activity's purpose" (p. 50). Further, these materials and tools "carry intelligence in them, in that they represent some individual's or some community's decision that the means thus offered should be reified, made stable, as a quasi-permanent form for use by others" (Pea, 1993, p. 53). The purpose of ECMs is to improve teachers' curriculum enactment for the purpose of student learning: the ECMs' affordances can be actualized through teachers' use. To function properly for the intended purpose, the ECMs must be designed to contain the knowledge and practices recommended by the community, such as the Next Generation Science Standards (NGSS Lead States, 2013) and/or the researchers' preferred direction for study.

From the cognition as information flow perspective, Perkins (1993) suggested analyzing materials that contain distributed intelligence in terms of knowledge, representation, retrieval, and construction. For ECMs, knowledge needed to enact a new curriculum encompasses subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge (Magnusson et al., 1999). In our digital ECMs, we added science content *knowledge* (e.g., plate tectonics, GPS systems, etc.), pedagogical knowledge (e.g., strategies for managing inquiry-based tasks, discussion prompts, etc.), and pedagogical content knowledge (e.g., embedded tools, exemplar students' answers, etc.). *Representation* involves text, symbols, inscriptions (tables, diagrams, and graphs) as well as real-world data visualizations used to convey the knowledge in ECMs. In our case, we added information in multiple forms: text, graphics, videos, annotated screenshots, and links to external sources to address teaching and learning plate tectonics. We also added the ability to easily access the embedded tools. *Retrieval* concerns the method in which teachers view, select, and access the information in ECMs. We embedded ECMs at various points in the module used by students. At the beginning of each student activity, teachers can read background information on science content and learning goals as intended by the curriculum developers. Throughout the activity, teachers can opt to click on tabs that expand to view additional information. All question prompts also have tabs that teachers can open to show exemplary student responses as well as rationales for multiple-choice answers and distractors. *Construction* refers to how all knowledge, representation, and retrieval methods are meaningfully organized as a whole. In our case, the ECMs were designed as a teacher-accessed overlay on the same module that students use. This construction is employed throughout the module, allowing teachers to find the same types of information in similar places. See, Figure 1.

Perkins (1993) emphasized that, for distributed intelligence to work, all four characteristics should work in consort: "needed knowledge, accessible representations, efficient retrieval paths, and constructive arenas that support . . . . The structuring of ideas" (p. 96) and cautioned that the mere presence of these elements in the materials does not guarantee that learning will be achieved. Salomon (1993) argued that learning emerges from the interaction between distributed intelligence and the individual's cognition, emphasizing the interaction between the teachers and the ECMs as a prompt for teacher learning about a new curriculum.

As such, we suggest that teachers' attaining the knowledge needed to enact a new curriculum involves three processes: (1) teacher usage captured in the amount, type, and timing of ECM features, (2) teacher sensemaking of the ECM information in their own teaching, with the goal of increased student learning, and (3) teacher reflection on their experience from the classroom and on their use of the ECMs. The access and sensemaking of the ECM information depends on each teacher's own prior knowledge and background as well as the prior knowledge and background of the students they teach. The first research question of this study addresses how teachers' background and experience relate to their use of digital ECMs. We used log data associated with ECMs and teacher demographic survey information for this research question. We hypothesized that teachers with fewer years of teaching experience, with teaching credentials outside of Earth science, and who teach students at the middle school level would access ECMs more frequently than those without these characteristics (e.g., more experienced teachers, teachers with

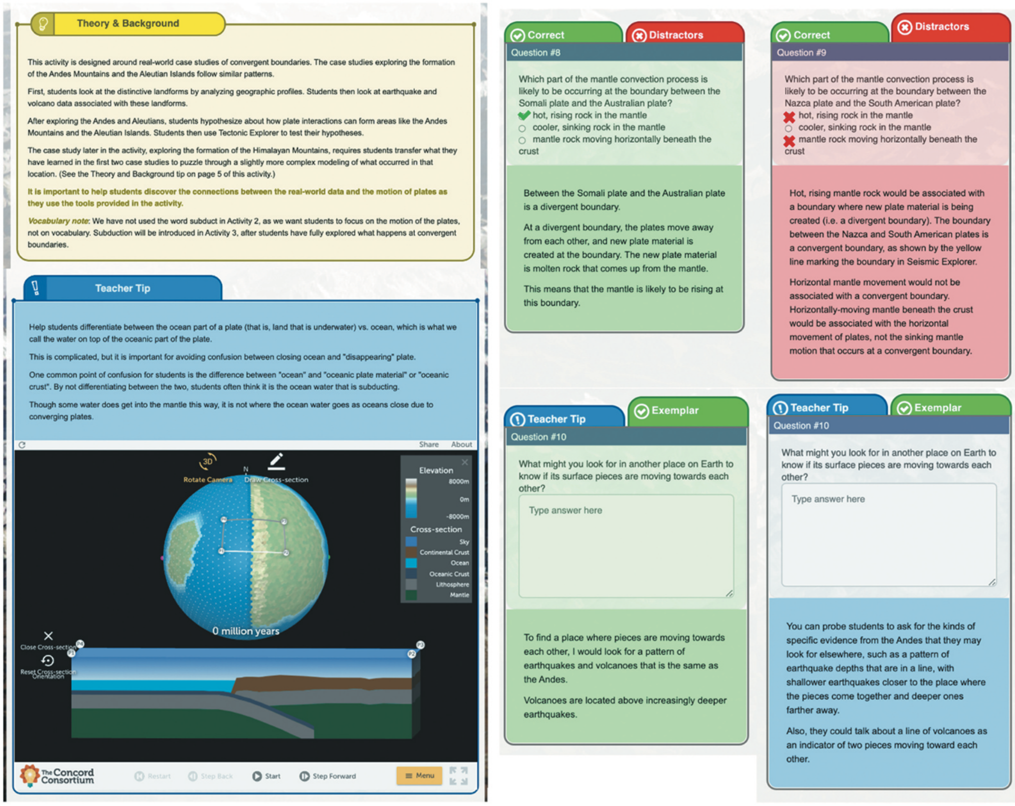

Figure 1. ECM tips expand and contract with a click. Left top: An expanded theory and background teacher support tip frames the activity for teachers. Left center: A tip on the Tectonic explorer points out a potential area of confusion for students. Left bottom: The Tectonic explorer embedded tool can be used by teachers. Right top: A tip within two multiple-choice questions after use of the seismic explorer. Correct tips give additional information on the correct choice. Distractor tips help explain misconceptions that students may have that led them to select an incorrect answer. Right bottom: The exemplar answer and teacher tip are expanded for the same open response prompt.

credentials in Earth science, and high school teachers). The second research question concerns the relationship between teachers' use of ECMs and student learning outcomes. We hypothesized that the more teachers accessed ECMs, their students would make greater gains from pre- to posttest on plate tectonics concepts. We investigated the third research question, related to which ECM features teachers found most valuable and why, using teachers' reflections and interviews. We hypothesized that teachers would find the exemplar answers the most useful, functioning as an answer key for use while assessing students work.

(1) How do teachers' background and teaching experience relate to use of digital ECMs?
(2) What is the relationship between teachers' use of the ECMs and student learning gains?
(3) Which ECM features did teachers find valuable and why?

The research context

The plate tectonics module was developed to teach plate tectonics as the unifying theory that explains how various geological phenomena on Earth's surface are the result of plate motion driven by the upper mantle system (Pallant et al., 2020). The five-activity module takes approximately eight class periods to implement and features progressively more complex, inquiry-based investigations to help students answer the driving question, "What will Earth look like in 500 million years?" See, Table 1 for the learning goals of the curriculum module. To provide students with opportunities to investigate tectonic phenomena, we developed two online tools. First, Seismic Explorer (SE) allows students to investigate real-world earthquake and volcanic eruption data on a world map. Second, Tectonic Explorer (TE) is an interactive simulation that allows students to experiment with plate arrangements on a three-dimensional Earth-like planet and observe changes on the planet's surface. Both tools provide students with a unique cross-section view, allowing observations of what happens below the surface.

Three types of ECM features can be accessed by teachers: teacher support tips, student support tips, and embedded tools. There are 224 tips strategically inserted in the module to support teachers' learning of the scientific content and "help teachers to learn how to listen to and interpret what students say, and to anticipate what learners may think about or do in response to instructional activities" (Ball & Cohen, 1996, p. 7). Because the instructional activities rely on the effective use of the two embedded tools, SE and TE are also available to teachers in the ECMs and are included as an integral feature of this study.

Teacher support tips apply to the entire activity in which they appear, opening and closing like window shades. They support teacher learning by providing subject matter and pedagogical content knowledge needed to teach the module (Shulman, 1986). Teacher support tips provide background information on science content and include images, videos, and links to outside resources as well as the rationale behind choices in pedagogical approaches. For example, theory and background tips appear at the start of each new activity to help frame the activity for teachers so that they can, in turn, frame it for their students.

Table 1. Subject matter learning goals of the plate Tectonics module and number of multiple-choice items related to each learning goal in the pre- and posttest.

Learning Goals	No. of Items
(1) Earth is covered in tectonic plates.	1
(2) Over Earth's history, the surface of the planet has changed, and will continue to change, due to the motion and interaction of these plates.	1
(3) Plates move in response to convection currents in the mantle that are caused by changes in heat and density.	3
(4) As tectonic plates move, they interact with other plates along all their shared boundaries.	2
(5) At divergent boundaries, plates pull apart and new crust is formed. There are shallow earthquakes and magma eruptions. Oceanic ridges and continental rifts are formed.	2
(6) At convergent boundaries, two plates come together with the denser plate subducting under the less dense plate. There is a diving pattern of earthquakes that follows the subducting plate as well as volcanic eruptions. Mountains and island arcs are formed.	3
(7) At transform boundaries, two plates slide past each other. There are numerous earthquakes. Linear faults and valleys are formed.	1
(8) The locations and types of plate boundaries can be inferred by observing landforms and patterns of geologic events.	3

Student support tips are tied to specific elements on each activity page. These tips address how to support students as they use simulations, collect and interpret data, make claims, reason about evidence, and write explanations. Student support tips are presented as tabs attached to the elements on the page, including embedded questions and digital tools. For example, open-ended questions may include an exemplary student answer and a tip intended to help teachers anticipate where students might struggle (Dove, 1998; Francek, 2013). These tips also include what information students should extract from SE and TE and how teachers can support students in connecting their observations to larger concepts. Table 2 lists the four types of teacher support tips and four types of student support tips included in the module.

Effective ECMs increase teachers' familiarity with pedagogy, assessments, and student activities (Merchie et al., 2018). The student activities in the module revolve primarily around the use of the *embedded tools*, TE (Figure 1) and SE (Figure 2). The ECMs were intentionally designed as an overlay on the student module, rather than a separate online teacher guide, to promote teachers' active engagement with the resources designed for students (Remillard, 2005). As such, the embedded tools appear in both the ECMs and the student module. Teachers are encouraged to use the embedded tools themselves, to conduct the same investigations as their students by running the simulations, and to become familiar with their parameters and settings.

Classroom observations and teacher feedback of early versions of the module (McDonald et al., 2020) informed the development of the content, breadth, and depth of the teacher and student support tips. We also consulted the design heuristics described by Davis and Krajcik (2005) and fully implemented three design heuristics. Because the module relies on graphical representations including the embedded tools, SE and TE, the first heuristic concerns *supporting teachers in using scientific instructional representations*. While basic instructions on using the embedded tools are available to both teachers and students, additional tips are provided to teachers that explain each digital tool and its use, including the types of data exploration that each affords. Features of the data visualizations and simulations are revealed to students in stages throughout the module, as are tips for teachers using the

Table 2. Teacher support tips and student support tips.

Category	Tip Name	Description
Teacher support tip	Theory & Background	Scientific content and pedagogical strategies, as well as explanations for design decisions in the module
	Discussion Points	Prompts for discussion questions that direct teachers to bring students together to talk about new and evolving concepts
	Digging Deeper	Ideas for directing students to more in-depth material related to the content
	General Teacher Tips	Catch-all tips, including reminders to check on student progress and strategies for supporting learning with the tools embedded in the module
Student support tip	Open Response Exemplars	Tabbed tips attached to each open response question with high-level example student responses
	Multiple-Choice Correct Explanations	Tabbed tips attached to each multiple-choice question that show the correct answer as well as a justification for that answer
	Multiple-Choice Distractor Rationales	Tabbed tips attached to each multiple-choice question that show the distractor answer choices and give reasons why selecting these answers signals a specific misunderstanding
	General Teacher Tips	Connected to questions, simulations, or visualizations, these tips provide (1) ideas on how to help students who have answered questions incorrectly advance their understanding of the material and (2) ways to help students interpret and find meaning in multimedia elements

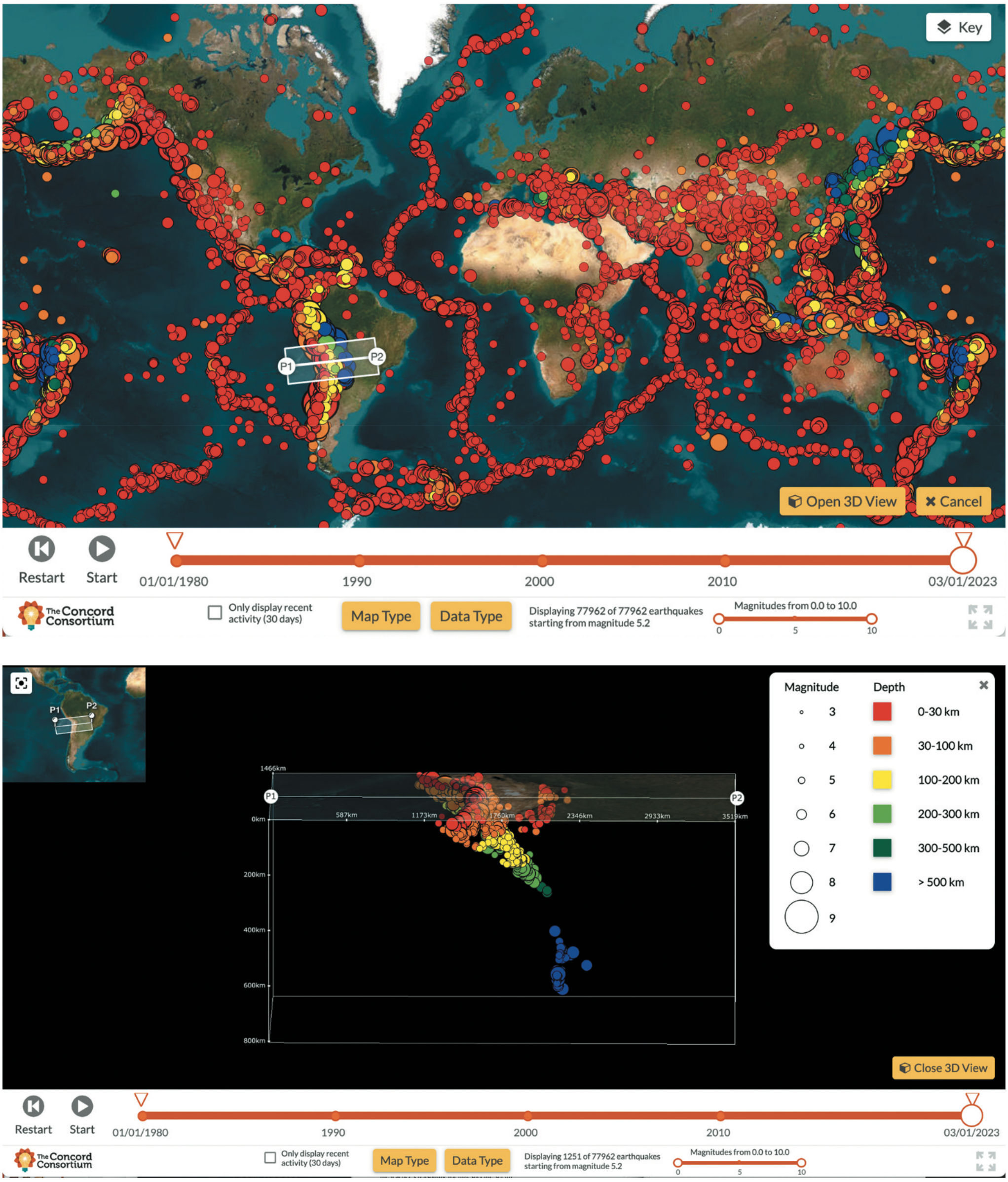

Figure 2. Seismic explorer is one of the embedded tools that allows for exploration of earthquakes and volcanic eruptions. Top: The world map shows earthquakes over time. Students draw a cross-section over an area with multiple earthquakes. Bottom: The 3D cross-section shows the depth of earthquakes, which reveals the edge of a subducting plate.

ECMs. These tips were purposefully designed to support teachers as they explored the module and used the embedded tools, so they would feel comfortable when using these technologies with students.

The second heuristic, *supporting teachers in engaging students with collecting and analyzing data*, was integral as the tools embedded in the module are complex. Teachers must learn how to help students gather and interpret the data and evidence produced by the tools. With suggestions at point of use for each instance where SE and TE are embedded in the curriculum module, teachers are guided on how to use the tools and visualizations themselves and what issues to anticipate from their students' use. Tips that fall under this heuristic are used liberally throughout the module and are intended to build teachers' capacity to interpret and connect the patterns revealed by the visualizations and simulations.

Finally, the heuristic of *supporting teachers to engage students in making explanations based on evidence* is necessary to support student sensemaking with data. Open-ended questions, intended to elicit student reasoning about the data displayed in visualizations and simulations, are embedded throughout the module. Exemplary student responses are provided for each open-ended question with suggestions for teachers on how to improve student explanations. These exemplars were chosen from student answers collected during prior classroom implementations.

Methods

This study utilized a mixed methods research design where quantitative data were analyzed to identify the overall patterns and qualitative data were used to describe or explain the patterns.

Participants

We recruited teachers through conferences, Earth science teacher lists, and social media. Eighty teachers from 35 states applied. We removed those with incomplete applications, unreliable access to technology, small class sizes (fewer than 10 students per class), and those with only one class section. This study focuses on 26 teachers who: (1) completed a pre-survey, (2) agreed to use the ECMs, (3) administered a student pretest, (4) actively facilitated the module with students, (5) administered the posttest, and (6) completed a teacher post-survey. In addition, 19 teachers agreed to participate in follow-up telephone interviews. No teachers received face-to-face professional development or training in how to use the materials or other direct classroom support from researchers. Teachers received a small stipend for their participation.

Among the teachers, 88% taught in public schools and 12% taught in private schools; 15% of the teachers' schools were located in urban settings, 50% in suburban settings, and 35% in rural settings. All but two teachers were White. They had spent an average of 17.14 years teaching (SD = 8.73), ranging from 5 to 35 years. Twenty teachers had teaching credentials in sciences other than Earth science. Six teachers also had Earth science credentials, one of whom had specific geology credentials. Fifteen teachers taught in middle schools; ten teachers taught in high schools; and one taught freshmen at a community college. For the purposes of our analysis, we added the community college teacher to the high school group as she indicated that her students performed at the high school level. The average grade of students, based on 1,102 students who provided demographic information, was 8.40 (SD = 1.64), ranging from 6th grade to 13th grade; 52.9% were female, 42.8% were male, 4.3% selected "other" or "prefer not to answer" options; 12.5% spoke English as a second language; 65.7% reported having used computers for science learning prior to the module.

Teachers taught the module as part of Earth, space, environmental, interdisciplinary, or general science classes, and reported that their curriculum choices were determined by NGSS (69%), state standards (62%), and district curriculum guidelines (42%). Prior to implementing the module, 77% had at least some experience with scientific argumentation using the claim-evidence-reasoning framework; 73% had at least some experience using data visualization and simulation tools in science class. Most teachers (77%) started the module without separately introducing plate tectonics content. Fifty-Eight percent used the module as a replacement, while 42% used it as a supplement. Teachers took between 8 and 10 class periods (approximately 45 minutes each) to implement the module. These data were collected in the 2018–2019 school year.

Data collection

Log data

Both the module and the ECMs were instrumented to collect, timestamp, and save all user interactions. Each time an individual teacher opened an ECM feature, the action was recorded and added to an electronic log file. Forty-Seven different types of user interactions were recorded with the ECMs, which we categorized into four groups: navigation, using tools, using tips, and answering question prompts. Nine navigation actions were recorded, including when a teacher opened or exited a page, viewed the table of contents, or moved to the next activity. These actions provided information on which activities in the five-activity module each teacher visited. There were 27 embedded tool events that recorded teachers' actions in SE and TE such as "clicked in the simulation window," "3DViewOpened," and "playClicked." Nine tip events showed when a tip was loaded, opened, or closed, as well as additional information about the specific type of tip (e.g., correct, distractor, exemplar, etc.). Finally, there were two events recorded that indicated that teachers were entering answers into the question prompts field. The contents of those fields were not recorded due to a technical limitation.

Each teacher action in the ECMs created a single entry in the log file with a timestamp. Therefore, the greater the number of entries, the greater the teacher's interaction with the ECMs. The total entries associated with the ECMs ranged from 0 to 4,558. All 47 action types were included in the total entry counts. Custom algorithms were written to parse these files further. The navigation actions were used to determine the specific activities and pages teachers visited. The logs were further analyzed to determine which tips teachers opened, which tools they used, and when these actions occurred. The question prompt actions were not analyzed as it was impossible to know what teachers entered into those fields.

Student logs of work in the module were also collected. Student actions and responses were not analyzed for this study; rather, their logs were used to determine the timing of teachers' ECM use. Finally, student logs of both the pre- and posttests were also collected. By combining these files and comparing timestamped actions between the module, the ECMs, and the assessments, it was possible to determine whether the teachers used the ECMs prior to, during, or after their classroom implementation. See, Figure 3. All actions occurring prior to students starting the module were coded as preparation. Teacher actions within five minutes of the majority of their students starting an activity in the module and logging out were

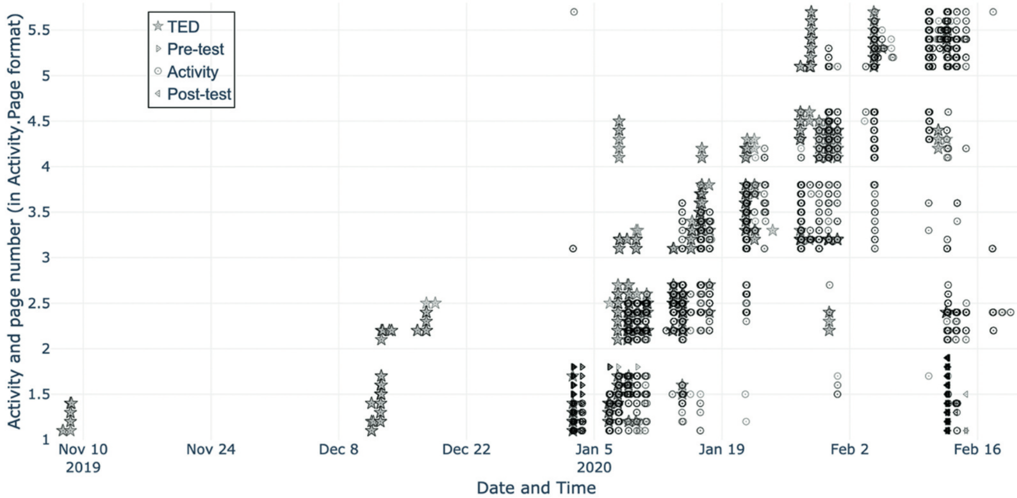

Figure 3. The graph shows teacher use of the ECMs, student activity in the module, and pre/posttests for one teacher's classroom. The y-axis shows actions on specific activities and pages within the module. Stars represent teacher actions in the ECMs. Dots show student actions in the module. In this example, we see the teacher used the ECMs in November and again in December to prepare for implementation. Students did not use the module until January. Overlapping stars and circles show when teachers and students were on the same activity page, using the module and the ECMs at the same time. During this period, stars alone indicate teacher use between class periods.

used to determine actions during a class. Teacher actions made outside this five-minute range were coded as actions between classes rather than during a class.

Teacher reflections collected from post-implementation survey

A 40-question online survey collected demographic data, past teaching experience and credentials, and information on the grade level band taught (middle school vs. high school). Eight questions asked teachers to reflect and give feedback on their experience using the ECMs. Teachers were asked to rate the features in the ECMs from least to most helpful and explain why, to describe how they used the ECMs both prior to and during class time, and how the ECMs helped them, if at all. See, Table 3.

Teacher reflections collected through interviews

We used teachers' reflections related to their ECM use to anchor the follow-up telephone interviews. Nineteen teachers were interviewed for approximately 30 minutes each and asked to clarify and expand on their responses to the post-survey. The three questions they were asked about the ECMs (called the "Teacher Edition" from the teachers' perspective) were: (1) How did you use the Teacher Edition to prepare for your implementation?, (2) What was the most helpful part of the Teacher Edition?, and (3) When and how did you use the Teacher Edition? Before class? After starting work with students? We applied the themes found in teacher reflections to the analysis of interview transcripts.

Table 3. Teacher post-survey questions about the ECMs.

Q.1 How much of the Teacher Edition module did you use?
- (a) I used all or most of the activities in the Teacher Edition module.
- (b) I used some of the activities in the Teacher Edition module.
- (c) I used just a few of the activities in the Teacher Edition module.
- (d) I didn't use the Teacher Edition of the module.

Q.2 How much time, in total, did you spend reviewing the Teacher Edition *before* using the module with students?
- (a) I didn't use the Teacher Edition.
- (b) Less than 30 minutes.
- (c) Between 30 minutes and 1 hour.
- (d) Between 1 and 2 hours.
- (e) Between 2 and 3 hours.
- (f) Between 3 and 4 hours.
- (g) More than 4 hours.

Q.3 After you started implementing the Plate Tectonics Module with students, how often did you go back and look at the teacher support materials (Teacher Edition and other supporting documents)?
- (a) Every day
- (b) Most days
- (c) Some days
- (d) Rarely or never

Q.4 We know that teachers come to our materials with different levels of background knowledge on various topics. We hope to provide resources that will be helpful to a broad range of teachers as they prepare to teach a diverse range of students.Were the extra materials provided in the Teacher Edition helpful to you as you prepared to teach the topic of plate tectonics? Please explain why or why not.

Q.5 If you did go back to the teacher support materials, what did you go back for? Please list all the materials that you can remember.

Q.6 Please rate each part of the Teacher Edition from most helpful to least helpful. (Five-point scale: Least helpful, Less helpful, Somewhat helpful, Very helpful, Most helpful)
- (a) Theory & Background information on scientific content
- (b) Theory & Background information on pedagogy
- (c) Discussion Points to help lead class discussions
- (d) Correct/distractor information on multiple-choice questions
- (e) Links to external resources (articles/videos)
- (f) Exemplar answers on free response questions

Q.7 Did you use the Teacher Edition during class time? (e.g., Did you refer to tips, exemplars, multiple-choice distractors, or background material while your students were using the module?)
- (a) Yes
- (b) No

If you answered yes, please describe what you used during class time and how it helped you.

Q.8 Did you share any of the materials in the Teacher Edition with your class? (e.g., Did you show students your computer screen or project a page from the Teacher Edition for the class?)
- (a) Yes
- (b) No

If you answered yes, please describe what you shared with the class.

Student pre- and posttests

We developed an instrument to assess student understanding of tectonic processes and phenomena such as the formation of landforms, the occurrence and formation of seismic activities, and the motions of plates near convergent, divergent, and transform boundaries in terms of thermodynamic and gravitational forces. The instrument consisted of 16 multiple-choice items, which mapped onto the curriculum learning goals (Table 1). Figure 4 illustrates three multiple-choice items used in the instrument. Six multiple-choice items were scored as 0 for scientifically incorrect understanding and 1 for scientific understanding. The remaining 10 items were scored 0 for incorrect, 1 for partial, and 2 for complete scientific understanding. The maximum score students could receive was 26. Reliability of the instrument was 0.74 using Cronbach's alpha, which is respectable according to DeVellis (1991). The average item discrimination index was 0.48, ranging from 0.21 to 0.84. All but three items had item discrimination indices greater than 0.30, which have

Question. Which of the following statements best describes how these broken pieces (plates) on the surface of Earth move?

(1) Plates stay where they are and do not move.
(2) Plates move sometimes and do not move other times.
(3) Plates are moving slowly and their direction is affected by nearby plates.
(4) Plates are moving slowly all the time and freely in all directions.
(5) Plates moved in the distant past but they do not move today.

Question. Which of the following caused the separation of Africa and South America?

(1) Earth's gravity
(2) Earth's magnetic field
(3) Heat currents beneath the surface
(4) Earthquakes and volcanoes
(5) Wind, waves, and erosion

Question. The figure below is a cross-section of the Pacific Ocean showing tectonic plates and plate boundaries. In which of the following regions is one plate moving away from another plate? Select all that apply.

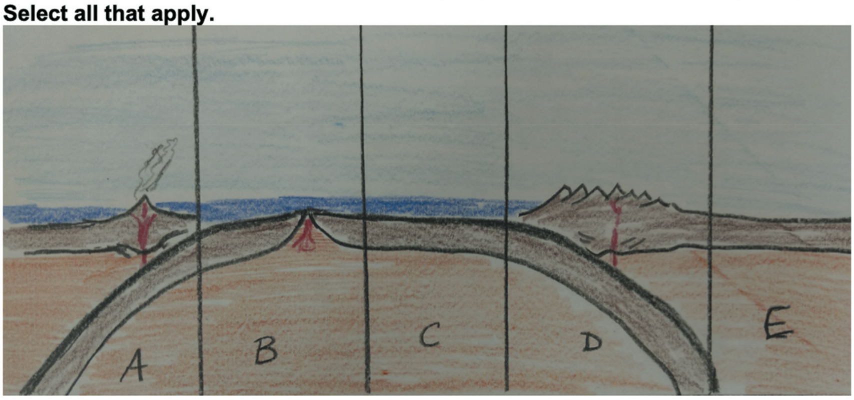

Figure 4. Three assessment item examples used in the plate tectonics pre- and posttests.

good abilities to differentiate between students who knew the plate tectonics content and those who did not. Validity refers to "the degree to which evidence and theory support the interpretations of test scores for proposed uses of tests" (American Educational Research Association, American Psychological Association, National Council on Measurement in Education & Joint Committee on Standards for Educational and Psychological Testing (U.S.), 2014, p. 11). This instrument was designed to capture the extent to which the students taught by each teacher made gains on the plate tectonics understanding targeted by the Plate Tectonics Module. To represent how much each student understood target plate tectonics concepts at the time of testing, we created a total accumulated score by summing up all scores received across 16 multiple-choice items (Mislevy et al., 2003). The difference between pretest and posttest represents the gain in student understanding of target concepts in plate tectonics listed in Table 1.

The identical instrument was administered as a pretest and a posttest: 1,238 students took the pretest and 1,171 students took the posttest. For each teacher, the student learning gain (Effect Size, ES for short) was calculated as Cohen's d which is the mean difference divided by the pooled standard deviation between pretest and posttest.

Data analysis

To answer the first research question related to teachers' use of the ECMs, we looked at usage logs to determine the number of activities that teachers accessed and the total number of logged events each teacher produced while interacting with the ECMs. In addition, we determined the number of logged events produced when teachers interacted with teacher support tips, student support tips, and the embedded tools. We compared teacher access to ECMs by the level of their students (middle school vs. high school), teaching certification (general science vs. Earth science), and years of teaching experience (in three ranges: 1–10 years, 11–20 years, 21+ years). We used independent-samples t-tests when the number of subgroups was two and ANOVAs when the number of subgroups was three in order to examine the presence of significant differences in ECM uses by these three factors. Using student and teacher log files, we identified whether teachers accessed the ECMs prior to students starting the module, in class while students were using the module, or between classes without students.

The second research question addressed the relationship between student learning outcomes and teachers' use of the ECMs. To answer this question, we obtained correlation coefficients between the number of times each teacher accessed the ECM features and student learning gains. Using a series of independent samples t-tests, we compared student learning gains between teachers who used EMCs prior to class, during class, and in between classes as compared to their counterparts.

We used teacher reflections and follow-up interviews to answer the third research question concerning teacher perspectives on using the ECMs. We carefully read the teachers' responses to survey Questions 5 and 6 as well as the explanations to Questions 7 and 8 (Table 3). Two authors of this paper then identified and named 13 different themes that emerged from the teachers' responses to each question. The themes were then reviewed with a third author. After thorough discussion, the group came to an agreement to consolidate into five common themes. To validate these themes, we used the transcribed teacher interviews.

Results

Identifying teacher usage of the ECMs

Among 26 teachers, log files revealed that 14 teachers (54%) accessed the ECMs in all five activities of the module while two teachers did not use the ECMs at all. Three teachers accessed the ECMs in four activities; three in three activities; one in two activities; and three in only one activity. Overall, teachers accessed the ECMs across an average of 3.69 activities ($SD = 1.76$). The average number of total teacher actions taken in the ECMs was 526 ($SD = 524$). Table 4 shows the differences in the total number of teacher actions by school level, teaching credentials, and years teaching. Middle school teachers accessed the ECMs significantly more often than high school teachers, $t(24) = 3.15$, $p < .01$. The average number of actions for teachers with non-Earth science certification was greater than those with Earth science certification, but this difference was not statistically significant, $t(24) = 0.35$, $p = .73$. The number of actions for teachers with more than 20 years of teaching experience was higher than teachers with 1–10 or 11–20 years of teaching experience; however, this difference was also not significant, $F(2,23) = 1.85$, $p = .18$.

Table 4. Mean comparisons of teacher actions by school level, teaching certificate, and teaching experience.

	n	Teacher Support Tips M	Student Support Tips M	Embedded Tools M	All actions M
(1) Grade level					
Middle (5–8 grade)	15	41	107	67**	744**
High (9–13 grade)	11	22	77	16**	228**
(2) Teaching credentials					
Science other than Earth science	20	33	94	50	546
Earth science specific	6	31	97	32	459
(3) Teaching experience					
1–10 years	7	26	54	37	425
11–20 years	10	31	107	32	362
21+ years	9	40	112	66	785

**significant mean differences at $p < .01$.

We also compared the teacher actions associated with each type of ECM. Table 4 shows that the number of embedded tool-related actions was significantly different between teachers teaching middle school and high school, $t(24) = 3.41$, $p < .01$. Middle school teachers used the SE and TE tools more frequently than high school teachers. There were no significant differences in the number of times teachers accessed teacher support tips or student support tips either by teaching credential or years of teaching experience.

We combined the log files for each teacher and their students to produce an interwoven series of timestamped ECM, module, pretest, and posttest events. We then created plots to illustrate the timing of each teacher's use of the ECMs as well as their students' actions in the module, pretests, and posttests. (See one example in Figure 4.) We used these plots to identify when teachers used the ECMs relative to their actual teaching time with students in class. We characterized two clearly distinct periods: ECM use as preparation for implementation and ECM use during implementation. We determined that 16 of the 26 teachers used the ECMs prior to the implementation period and 21 of the 26 teachers used the ECMs during the implementation period. We then used log analysis to find that of those 21 teachers, 11 accessed the ECMs during class while 10 accessed the ECMs only between class periods.

Since we found a significant difference between middle and high school teachers in terms of their use of the ECMs, we investigated if there were differences in the timing when each group used the ECMs. The mean number of middle school teachers' interactions with the ECMs was greater than those of high school teachers at every time period: prior to students starting the module, during class time, and between classes. In particular, middle school teachers' in-class interactions with the ECMs ($M = 235$) were significantly higher than high school teachers ($M = 15$), $t(24) = 2.46$, $p < .05$. For preparation, there were no significant differences between middle school teachers ($M = 197$) and high school teachers ($M = 92$), $t(24) = 1.34$, $p = .19$. Similarly, there were no significant differences in between-class interactions with the ECMs for middle school teachers ($M = 311$) and high school teachers ($M = 120$), $t(24) = 1.89$, $p = .07$.

Connecting teachers' use of the ECMs and student learning gains

Students in each of the 26 teachers' classes showed significant pre/posttest gains, ranging from ES = 0.36 SD to 2.59 SD. There is a slight positive correlation between the number of teacher interactions with the ECMs and student learning gains measured in Cohen's d (Effect Size), r = 0.20, but it is not significant (p = .32). We also calculated correlations between student learning gain and teacher use of the three types of ECMs: teacher support tips, student support tips, and embedded tools. There were no significant correlations between student learning gain and teacher support tips, r = 0.03, p = .89; between student learning gain and student support tips, r = 0.08, p = .69; or between student learning gain and use of embedded tools, r = 0.26, p = .19.

We also looked at whether the timing of ECM use made a difference in student learning gain. The student learning gain was significantly higher for the 11 teachers who used the ECMs in class while their students were using the module (ES Mean = 1.35 SD) than for the 15 teachers who did not (ES Mean = 0.82 SD), t (24) = 2.42, $p < .05$. There was no significant difference whether teachers used the ECMs for preparation (n = 16, ES Mean = 0.99 SD) or not (n = 10, ES Mean = 1.14), t(24) = 0.61, p = .55. Similarly, there was no significant difference in student learning gain whether teachers accessed the ECMs between classes (n = 21, ES Mean = 1.11 SD) or did not (n = 5, ES Mean = 0.76 SD), t(24) = 1.21, p = .24.

Teacher feedback on educative curriculum features in the ECMs

Five major themes were identified in teachers' responses to post-survey questions. Teachers reported that the ECMs helped them: (1) review and, in some cases, learn the content before they started, (2) understand the design and intent of the module, (3) become familiar with the embedded tools and curriculum, (4) prepare to help students work through complex concepts and build understanding, and (5) guide students during class time both in answering module questions and in classroom discussions.

First, the ECMs appealed to teachers at all levels of experience as "a good review" of the content. One teacher with less background in plate tectonics said the ECMs were helpful because "Earth science is my least familiar discipline." Another teacher said, "Even with a substantial background I found the materials very useful." Second, because the module has a unique way of teaching plate tectonics as the underlying theory of geology, teachers indicated that the ECMs helped them recognize the "perspective of the module" and gave them "confidence to use it" with students. Third, because the ECMs are built on the student module, teachers said they appreciated having time to experience the curriculum and embedded tools from the student's perspective. One teacher indicated that she reviewed the ECMs prior to each class to determine good places to pause students and have class discussions, where to focus their attention, and what was important for them to understand before moving on. Fourth, teachers felt that the ECMs prepared them to help their students work through complex concepts, often through additional discussion. One teacher said the ECMs were helpful "when students came to me with issues and/or concerns, for clarification and suggestions as to how to untangle their thoughts." Finally, teachers used the exemplar answers and multiple-choice rationales during class to "focus students in the right direction" or "approach the information in a different way" if they were struggling with a particular question.

Teachers were also asked to rate features of the ECMs from least helpful to most helpful (see Question 6 in Table 3). We collapsed the top two and bottom two categories such that we used three categories for the analysis. The mean rating of all the features was between 2 (somewhat helpful) and 3 (most/very helpful). Exemplar answers to free response questions were rated most highly of all the ECM tips (M = 2.92), which is what we expected, followed by classroom discussion prompts (M = 2.77), and explanations of multiple-choice questions including both correct and distractor rationales (M = 2.58). The mean usefulness rating of the information on science content was 2.50, while that of the links to external resources (articles/videos) was 2.30. Information on pedagogy was the least helpful (M = 2.15).

Discussion

To support teachers' enactment of a new technology-enhanced science curriculum, we designed ECMs in such a way that their educative features were at the teachers' fingertips with one-click access on the same page as their students rather than in a separate teacher guide or lesson plan. In addition, the online format allowed flexibility in how and when teachers could access the ECMs. Through combining log files from teachers and students, we uncovered what types of teachers accessed the ECMs, when, and how often; which parts of the ECMs teachers accessed; and the potential relationship between the amount of ECM access and student learning outcome. We discuss results of this study along with methodological affordances and limitations of using log analysis in ECM research for curriculum-based science reform.

Teacher characteristics and ECM use

Like prior studies (Arias et al., 2016; Remillard, 2005), we found that ECMs embedded in the module were used to varied extents by teachers with different backgrounds and experience as they worked to attain the knowledge necessary to enact the module. In the design of ECMs, we targeted teachers with less teaching experience and less Earth science background knowledge. However, our results show that the only characteristic that mattered was whether the teacher was teaching at the middle or high school level. We speculate that middle school teachers accessed the ECMs more frequently because they might not have the same in-depth subject matter knowledge that high school teachers have (McConnell et al., 2013), that they might have had more flexibility in their schedules, or that younger students worked less independently and needed more direction from their teachers (Schweder & Raufelder, 2019). This finding adds support for building digital ECMs into the growing body of online curriculum materials designed for teaching complex science topics to middle school students. Such digital ECMs could be used by middle school science teachers who lack content knowledge, do not have access to other training opportunities, or need "just-in-time" support in the classroom. To what extent these ECMs can help these teachers is fodder for future research.

ECM use and student gains

The goal of ECMs is to provide the teacher training necessary to enact new curriculum and new pedagogical approaches to enhance student learning outcomes. Darling-Hammond

(2010) found that the teacher training opportunities deemed most valuable by teachers include those that provided hands-on experience, offered extended content knowledge, and showed how to teach new materials to students. Past studies (Bates & Morgan, 2018; Darling-Hammond et al., 2017) found that including these features supported both teacher and student learning. Our ECMs provided all three features via access to embedded tools, domain-specific knowledge, and pedagogical strategies. Our study shows a non-significant positive correlation between the total use of the ECMs and student gains across the 26 teachers we studied. However, there are many factors that go into teaching with a new curriculum beyond content knowledge and pedagogical content knowledge, including factors pertaining to a teacher's specific beliefs or goals as well as to specific needs of their school population (Davis et al., 2017; Desimone, 2009; Remillard, 2005; Roehrig et al., 2007). As such, the correlation was tenuous at best.

However, we also compared student learning gain by the timing of ECM use across teachers. Traditional ECMs are accessed more frequently by teachers prior to classroom instruction (Sherin & Drake, 2009). We found that 11 teachers in our study used the ECMs in class at the same time that their students worked on the module. This is in contrast to the study by Duncan et al. (2011), who reported that no teachers used their embedded online ECMs during class time. Based on teacher reflections collected from post-implementation surveys and interviews, these teachers used ECMs during class time to assess student responses, lead classroom discussions, and assist their students in making sense of their investigations using the two embedded tools (i.e., SE and TE). These teachers may have been using the ECMs as a digital, real-time "inquiry partner" (Gerard et al., 2016) to help them clarify student ideas as well as build explanations based on the visualizations. The learning gains for the teachers who used the ECMs during class were significantly higher than those who did not. We hypothesize that teachers' use of the ECMs while students were also working with the materials may indicate that teachers are actively engaged in facilitating inquiry-based lessons (Furtak et al., 2012; Kirschner et al., 2006). Additional studies could be focused on instructional mechanisms associated with how teachers' ECM use during class time facilitates complex, inquiry-based science learning.

Teacher reflections

We studied the difference in teacher access of specific ECM features: teacher support tips, student support tips, and embedded tools. We found that middle school teachers accessed the embedded tools significantly more frequently than high school teachers. Again, we speculate this difference may be because the embedded tools, SE and TE, are complex representations (McDonald et al., 2020; Pallant et al., 2020) of plate tectonics phenomena that require both in-depth understanding of the domain knowledge and pedagogical content knowledge. There were no differences in access to the teacher support tips and student support tips by teachers in terms of their teaching experience and area of teaching credentials. This suggests that teachers' past experience and background knowledge does not guarantee that they are prepared to enact a new curriculum (Ball & Cohen, 1999; Davis et al., 2017; Remillard, 2005). This is also corroborated by the experienced teachers who reported that ECMs offered a good review of the materials. This result shows that while ECMs may be designed for novice teachers, they can be useful for a broad range of teachers.

Two of the most useful ECM features rated by teachers address assessment knowledge in the form of exemplar answers to open-ended questions and rationales for correct and incorrect answers to multiple-choice questions. These teacher self-reports were corroborated by log data in the large number of clicks on exemplar answers to open-ended items provided in the ECMs. When we delved deeper into teachers' reasoning for why these were rated so highly and opened so frequently, teachers reported having more confidence in their ability to answer content questions, trust in their understanding and interpretation of the questions in light of the expected student performances with embedded interactive tools, and comfort with assessing students' reasoning and explanations during class time. Teachers valued the knowledge gained from the ECMs and passed it along to their students in interesting ways as demonstrated by one teacher who had students volunteer to teach parts of each activity using ECM features during the class. The student went to the front of the class, read each question, discussed the exemplar answers that the ECMs provided, and ran the simulations while thinking out loud. Again, we see that ECMs can play a role not only in teacher preparation but also during class time and posit that future ECMs could be designed with the goal to specifically support use in the classroom.

Log analysis method

Most studies on ECMs had a face-to-face component and relied on printed materials to deliver information (Arias et al., 2017; Beyer et al., 2009). Much of the teacher curriculum enactment research utilized in-person classroom observation (Arias et al., 2016; Gerard et al., 2010; McNeill & Pimentel, 2010). In this study, we used time-stamped computer logs to examine teacher usage of ECMs and student usage of the online curriculum for which ECMs were developed. This log data analysis method can reduce the amount of time and effort necessary in collecting enactment data with digital learning resources by first automatically recording both teachers' and students' actions as they interact with the digital resources and then computationally analyzing the records to identify patterns during the entire time period (Dajani, 2017; Pringle et al., 2017). This remote method is suitable for scaling up to larger studies of online ECMs. However, researchers must be cautious when carrying out studies with log data. Since log data capture the behaviors recordable through interactions, teachers' and students' cognitive processes cannot be accessed without prompting through interviews, surveys, or questions. Triangulation with other data sources is always necessary to interpret the results. Moreover, accepted theories must be evoked when making interpretations.

Limitations

The generalizability of the findings in this study is limited. Even though our data included a broad range of teacher and student demographics, we did not employ random sampling from the general population. If we had sampled other teachers, more accurate estimations or patterns could have been obtained. Nor did we employ an experimental design with a control group, so it could not be discerned whether our digitally enhanced ECMs worked more effectively than other ECM approaches or no ECMs at all. We did not study how teachers make sense of ECMs while they are reading or interacting with them on the spot. Detailed think-aloud studies can elucidate the sensemaking process with ECM features more clearly. The teachers in this study were using a new curriculum module and using the ECMs simultaneously. It would be interesting to follow teachers over multiple iterations to see if teachers continue to use the ECMs to the same extent or in the same way after multiple years of using the materials. Other research has shown that teachers do not use all the ECM features associated with new curriculum materials in their first implementation (Cervetti et al., 2014; Loucks-Horsley et al., 2009). A longitudinal study could explore which elements of the ECMs teachers use in subsequent iterations. Furthermore, research has found that professional development lasting more than one school year is most successful (Gerard et al., 2011). As part of professional learning, ECMs could be added to related geoscience curriculum modules to support teachers over the course of multiple topics, increasing their exposure and practice with ECMs. This would enable additional studies to investigate not only repeated use of the ECMs for the module, but for other modules as well.

Conclusion

By using log data of teacher interactions with ECMs, we were able to shed light on teachers' classroom enactment of curriculum materials and create a picture of teacher use of the materials without having to be present in the classroom. This allowed us access to all 26 teachers in this study at modest effort and cost. We used computer-generated log files that recorded teacher interactions with the ECMs, compared them with log files that recorded student interactions with the module (Gweon et al., 2015; Lee et al., 2021), and triangulated the patterns based on teacher self-reflections from post-implementation surveys and interviews. This study points to the promise of how log data can be explored to conduct research and improve both teacher and student materials alike.

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Human subjects approval

The research done in this study was approved by Ethical & Independent Review Services (approval number 18202-02). Signed consent was obtained as directed by the IRB.

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