JOURNAL OF GEOSCIENCE EDUCATION
2022, AHEAD-OF-PRINT, 1-15
https://doi.org/10.1080/10899995.2022.2071082

Scaffolding geology content and spatial skills with playdough modeling in the field and classroom

Kathryn M. Bateman[a], Joy Ham[a], Naomi Barshi[b], Basil Tikoff[b], and Thomas F. Shipley[a]

[a] Department of Psychology, Temple University, Philadelphia, Pennsylvania, USA [b] Department of Geoscience, University of Wisconsin-Madison, Madison, Wisconsin, USA

ABSTRACT

Spatial skills are embedded in all aspects of the geosciences. The teaching and learning of spatial skills has been a challenging, but vital, endeavor. To support student learning of spatial skills in undergraduate courses, we designed scaffolds for spatially dependent content in a mid-level geoscience course using playdough to allow students to model and manipulate geologic structures and processes. Using a semester-long geology course as a case study, we explore the ways in which students reported playdough supported their learning of geoscience content during the course. Students found the playdough most helpful for visualizing geologic structures, such as faults and domes, which students were then able to encode into their long-term memories, or “mental libraries,” for application to new contexts on assessments later. The playdough was more helpful at the start of the course when students were grappling with introductory course content and skills. Later in the course, the need for the playdough as a scaffold faded, as intended. Most students eventually sought new scaffolds, such as three-dimensional block models, which illustrate more complex and sophisticated structures and processes. Therefore, we see playdough as a useful scaffold for students in the early stages of spatial and geologic skill development as it aids students in developing both sets of skills. It is easy to utilize, inexpensive, portable, widely available, and familiar to most students.

ARTICLE HISTORY

Received 24 June 2021
Revised 24 April 2022
Accepted 25 April 2022

KEYWORDS

Modeling, scaffolding, spatial skills, undergraduate learning

CONTACT **CONATCT** Kathryn M. Bateman batema34@msu.edu Temple University, 1701 N 13th Street, 333 Weiss Hall, Philadelphia, PA 19122, USA.

Supplemental data for this article is available online at https://doi.org/10.1080/10899995.2022.2071082.

Introduction

The practice of geology is inherently a spatial process. Whether conducting field work, analyzing samples in a lab, or creating computational models, geologists work to explain spatial and temporal phenomena. In learning to become geologists, students process the spatial nature of the Earth as novice geologists while also learning the spatially grounded language needed to practice geoscience (Jaeger et al., 2017). Developing into an expert geologist requires spatial skills (Petcovic & Libarkin, 2007), but these are not easy to acquire. General spatial skills support many disciplinary tasks. For example, Kali and Orion (1996) found that students with less developed spatial skills were less skilled at geologic tasks such as making cross sections. This task requires the specific spatial ability to think in visually penetrative ways (Kali & Orion, 1996). Learning these crucial disciplinary skills can be challenging, but it is possible. Meta-analysis of studies on the teaching of spatial skills have shown that students’ spatial abilities are malleable, and training can improve students' spatial skills in transferable ways (Uttal & Cohen, 2012). As we prepare undergraduate students for futures in geoscience and engineering that demand advanced spatial thinking skills, we have the opportunity and responsibility to teach and practice spatially demanding tasks and scaffold their learning.

Spatial skills in geoscience

The diverse set of spatial skills utilized in geosciences include disembedding, visual penetrative thinking, mental animation, mental rotation, and perspective taking, among others (e.g., Manduca & Kastens, 2012). *Disembedding* is a key competency for geoscience in which one is able to focus on the most important aspects of a scene. When disembedding, the geologic observer must look at complex spatial scenes and determine what is important to give their attention to (Reynolds, 2012), such as focusing on which layers to examine in search for an unconformity. *Visual penetrative thinking* requires students to use visible surface structures to imagine the interior of an object, such as the three-dimensional orientation of faults beneath the surface of an outcrop. Visual penetrative thinking is needed for understanding many concepts in structural geology (Kali & Orion, 1996). In addition to disembedding and visual penetrative thinking, P. McNeal et al. (2018) found mental animation valuable for geoscientists working to understand aspects of the fluid Earth. *Mental animation* engages with geological processes, both temporal and spatial, to recreate the invisible past based on the observable present. This skill helps geoscientists imagine Earth processes that are happening or have happened to make predictions about the future (Hegarty & Sims, 1994).

Within the array of mental animation skills are two specific skills: mental object transformation and perspective taking. Object transformation includes mental nonrigid transformation (e.g., bending and breaking; Atit et al., 2013; Resnick & Shipley, 2013) and rigid transformations. The most extensively studied type of rigid transformation is *mental rotation,* which requires students to think about how an object would look if it were rotated into a new position without any internal changes. Many students are challenged by geologic tasks that require mental rotation, such as aligning map views with real world structures (Montello, 2010). Similarly, *perspective taking* requires students to imagine how an object or feature would look from a different point of view, but rather than mentally moving the object, they imagine moving themselves to visualize the structure from a new perspective. For example, astronomy students may be asked to imagine the night sky from a different location than Earth, thinking about that view from a new perspective (Plummer et al., 2016).

In this study, we add the skill of *visually connecting* to the skills detailed by Manduca and Kastens (2012), which requires linking together spatially separated rock structures by recognizing that rock layers used to be connected before erosion or faulting isolated them into separate outcrops. For example, geologists would need to mentally connect rock layers on one side of a valley with the other side to see the continuity of layers or structures. We added this skill because it is critical to the disciplinary tasks in field mapping courses and beyond, where a geologist is expected to infer the past or present location and structure of rocks from isolated surface exposures (e.g., in mining where such estimates would be used to guide the search for specific rock layers or ore bodies).

Learning spatial skills

Spatial skills can be developed in undergraduate geoscience courses even in the absence of explicit training. Ormand et al. (2014) found a 10% improvement across contexts and types of spatial skills measured (mental rotation, penetrative thinking, and disembedding) after completion of a geoscience course. These improvements occurred in the absence of an explicit change to the content or pedagogy from previous iterations of the course to focus on spatial skills. Hannula (2019) found similar results for students in field-related courses: students in an introductory field methods course, with no specific course activities targeting spatial tasks, improved their penetrative thinking skills. The course also closed the gender gap between male and female students' scores on the spatial skills metrics.

When tasks that are designed to improve spatial thinking are embedded in geoscience courses, students see their value. Gold et al. (2018) qualitatively assessed student perception (e.g., enjoyment, usefulness) of training modules in an undergraduate geoscience course focused on mental rotation, disembedding, and penetrative thinking. Gold and colleagues also found that students saw the tasks as "engaging their brain in new ways" (60%; p. 2216) and felt it improved their performance in either their geology courses or other courses (40%). These survey results were supported by measured improvement in spatial skills tasks for 70.5% of students (Gold et al., 2018).

Uttal and Cohen (2012) argued that spatial skills may be particularly important early in geoscience education and, because they are important at the novice level, are required for learners to become experts in the domain. Although other factors such as motivation and working memory capacity contribute to likelihood of retention in a discipline, the lack of spatial skills may be a specific barrier to early progress in geosciences. As students advance, these skills may become less important. Hambrick et al. (2012) found that spatial skill level did not predict success on a geology mapping problem for experts, whereas there was a strong correlation between spatial skills and success for novices.

Scaffolding spatial skills learning

While general improvements in spatial skills may come as a result of geology coursework, specifically scaffolding the learning of spatial skills in the course context has the potential to improve novice geologists' disciplinary work. Scaffolding occurs when work is shared between learner and some "other" to situate the learner in the "zone of proximal development" (Rogoff, 1990). This provides learners with the ability to reach beyond the bounds of what they could have otherwise achieved on their own (Pea, 2004; Wood et al., 1976). Although the field of the learning sciences has often defined scaffolds as another person or a piece of technology (see Pea, 2004 for a history), others in the field have asserted that we should think more broadly by defining scaffolds to meet the context-specific needs of learners (Palincsar, 1998). Here we consider the affordances of playdough models as a tool for geoscience instructors to scaffold novice geoscientists' development of spatial skills and spatial concepts in geology.

In the geosciences, scaffolding tasks that require spatial skills can support both learning content and developing spatial skills. Trying to make sense of geology with incompletely developed spatial skills can overtax cognitive load (Jaeger et al., 2017). Ishikawa and Kastens (2005) suggested breaking down these complex geologic and spatial tasks to better scaffold learning for novices. Another way to reduce cognitive load is by externally representing complex spatial relations. One method that geologists use to reduce cognitive load is creating sketches of processes and components (Johnson & Reynolds, 2005). Gestures and modeling can fully represent structures and processes and thus serve as important scaffolds for geoscience spatial skills (Gilbert & Osborne, 1980; Ping & Goldin-Meadow, 2010) because they can be used as the base for learning through analogies (Jee et al., 2010; Libarkin & Brick, 2002). Gestures have been observed to aid in spatial reasoning and in the application of spatial skills to spatial problems (Alibali et al., 2011; Atit et al., 2015; Ehrlich et al., 2006; Herrera & Riggs, 2013; Van Boening & Riggs, 2020). Similarly, using and constructing models can support the application of skills and the identification of parts of a rock structure (Reynolds, 2012). Visual penetrative thinking was scaffolded by providing students a concrete manipulable in the form of three-dimensional blocks (Kali et al., 1997; Reynolds et al., 2005, 2006; Reynolds & Johnson, 2002). Playdough as a scaffold in the current study combines the flexibility and transient quality of gestures with the permanence of models to reduce the cognitive load required to visualize geologic structures and processes.

Playdough as a learning scaffold

Playdough serves as an ideal tool for use in geoscience courses for its portability, accessibility, and potential to scaffold complex cognitive processes. We use the term "playdough" to refer to any reusable, colorful modeling compound. We used a commonly sold brand, Play-Doh™. Playdough allows instructors to craft models in the moment to meet the needs of the students and respond to students' observations, rather than predetermined areas selected for focus *a priori*. This flexibility can allow instructors to evaluate student needs to determine the most appropriate scaffolding, in line with learning science's tenets of scaffolding (Pea, 2004). Playdough also provides a physical representation to cognitively offload details and improve mental processing by simplifying the real variability of the solid Earth to a small number of discrete conceptual units. Representing a specific lithology with one color of playdough, for example, allows instructors to support students in identifying the most important part of the structure (e.g., lump together similar layers of rocks to highlight an unconformity; Reynolds, 2012).

Computer-based modeling tools are frequently used to scaffold student learning of geoscience and spatial skills. However, in many cases, these computer-based modeling tools are used in place of field experiences rather than as a supplement (e.g., Lin et al., 2012; Pallant & Lee, 2017). While technology-rich tools, such as augmented reality sandboxes (Woods et al., 2016), VR headsets (Klippel et al., 2019), and 3 D printing (Carbonell Carrera et al., 2017) can more elaborately or precisely model geological phenomena, they are expensive and difficult to take into the field. For example, Horowitz and Schultz (2014) outlined the ways that 3 D printing could be used to model geologic features, but this approach requires that faculty, and perhaps students, have funds to purchase these printers and the necessary software, become familiar with software needed to reconstruct a specific feature, and have the available data to reconstruct a feature of interest. This also requires planning ahead for the myriad challenges students may face in the classroom or field with a feature. Furthermore, the need to learn software and programming languages (e.g., Hepworth et al., 2020) to use these models, as well as having the personal computer capable of running them, creates barriers to accessing these types of models, particularly for students from first-generation college or low-income households who often do not have the social or financial resources to explore these areas prior to higher education (Rideout & Katz, 2016).

Playdough is inexpensive, familiar, transportable, and easily manipulated. Students can directly view the geology *in situ* in the field and simultaneously model what they see *and what they cannot see*. Playdough's low cost means the effect on budgets is minimal, and playdough is likely a familiar material to most students. The tactile, manipulable, colorful, and often nostalgic nature of playdough makes it an engaging and accessible tool for students, in the classroom and in the field. Given that, we pose the following questions:

1. How does the use of playdough as a scaffold foster core geologic spatial skills required for inferring spatial processes in an undergraduate geoscience course?
2. How does the usefulness of playdough models as scaffolds change over the duration of the course?

Research design

We employed a case study approach (Stake, 1995) to examine a mid-level geology course implementing an intervention. Taking Stake's constructivist approach to case study (Stake, 1995) allowed us to explore a naturalistic phenomenon, in the natural setting. The boundaries of case study do not have limits on case size: a case can encompass a single lesson, a department, or an event (Taber, 2014). We bounded our case in a mid-level course required for an undergraduate geology program, scaffolding the learning of spatially dependent geoscience content. We asked "how" questions (Yin, 2009) of this complex system of learning spatially dependent geoscience phenomena. Furthermore, we situated the learning in a social constructivist theory of learning, drawing on the tenet that the cognitive (spatial skills) and social (learning) cannot and should not be separated (Cobb, 1994).

Though single case studies are common in geoscience education, particularly those in efficacy of learning (e.g., Bitting et al., 2017; McConnell et al., 2017; St. John & McNeal, 2017), we believe that ours provides a deep, rich data set from which to draw interpretations of student learning in a single case (Allison & Zelikow, 1999; Yin, 2009). Our case study approach was relativist: we understand that these findings are specific to the time, place, people, and cultural norms engaging in the study (Guba & Lincoln, 1994).

Following Stake's approach to case study, we crafted our methodology to increase the validity through triangulation of data sources (variety of sources over time), investigators (interdisciplinary team), theory (variety of epistemologies), and method (observations, classroom artifacts, surveys, and assessments) (Denzin, 1978). An interdisciplinary team who were able to engage in discourse from multiple epistemic and ontological perspectives around the multiple data sources collected over time, enhanced the robustness of the data and the resulting findings.

To capture the interplay among Earth science content, learning, and the students' minds, our interdisciplinary team combined expertise in structural geology, spatial cognition, and science education. Two authors (Tikoff and Barshi) are geologists and served as course instructors. One author (Bateman) is a geoscience educator and co-designed course activities and observed field trips. The final two authors (Ham and Shipley) are cognitive psychologists who provided framing and analysis of the data corpus. By collaborating across disciplines, we mutually enriched and critiqued our collective work, bringing together ideas and frameworks from each of the three fields, aligning and checking one another's claims.

Our aim was to study model use *in situ* and collect students' reports to better understand *how* playdough might support student learning. Most studies reported in our literature review above were heavily reliant on pre/post-test analyses, often divorced from the details of the content and student experience of the course as a learning environment. The students' ideas and feelings about the scaffolds and learning of spatial skills were not always captured in prior studies. Examining students' perspectives on the efficacy of playdough in learning spatial skills can help identify what the students see as effective support, even when learning is not captured by performance on a specific test.

Study population and setting

This study was conducted as part of a mid-level undergraduate course (Introduction to Geologic Structures) at a large, Midwestern US university. For the Fall 2019 semester, 38 students were enrolled in the course. Students enrolled in the course were mostly white (35 of 37), male (25 of 37), juniors (16 of 37), and geoscience majors (32 of 37). Full demographic information for the class can be found in Table 1. The only prerequisite for Introduction to Geologic Structures was an introductory geology course. Introduction to Geologic Structures was a required course for the Geoscience major and a prerequisite course for Structural Geology, an upper-level major course. Non-majors enrolled in the course were taking this course as an elective, and one student was auditing the course and not included in demographic information. The course was a four-credit lecture/lab course which consisted of three one-hour lecture periods and one three-hour lab per week, two day-long field trips, and one three-day field experience.

Table 1. Demographic information for student participants (N = 37). (Table view)

Gender	Male	25
	Female	12
Major	Geoscience	32
	Non-geoscience	5
Race	White	35

	Asian	2
Class Year	Sophomore (2nd)	13
	Junior (3rd)	16
	Senior (4th)	8
Residency	In-State	16
	Out-of-State	15
	International	6

The objective of the course was to provide students with the skills required for professional geoscience work, which included reading topographic maps and geologic maps, recognizing and interpreting the history of landforms, and constructing cross-sections of complex three-dimensional geologic structures from geologic maps. Conceptually, the course aimed to develop three-dimensional thinking that can be applied to explain the evolution of geologic structures and landscapes. The complexity builds over the semester. Early in the course students identified rock types and formations, learned to use standard field instruments (e.g., Brunton compasses, hand lenses), and described geological phenomena. Over the course of the semester, students read increasingly intricate topographic maps, interpreted geologic maps, and constructed cross sections for progressively more complex geology. The course ended with integrative, challenging maps that required students to employ strategies they learned over the term and rapidly identify and visualize three-dimensional structures.

Recognizing the spatially dependent nature of the course, and geology in general, the research team made a decision to study how playdough models scaffolded students' developing understanding of geologic phenomena and skills. Playdough models were used to show structures (static models, Figure 1) or processes (dynamic models, Figure 2) in line with the goals of the course. For example, one major goal of the course was for students to learn to read and create cross sections. To better understand the three-dimensional nature of a topographic map of homoclinal dipping beds (Figure 3), the instructors created a playdough model (Figure 4) that made the flat, topographic map three dimensional, scaffolding students' visually penetrative thinking. This enabled conversations to occur comparing the structure in playdough and the topographic map. Students also used playdough to create their own three-dimensional structures from maps and cross sections to evaluate their own thinking.

Figure 1. Playdough model of the Pahasapa Limestone on Little Elk Creek Trail in the Black Hills, SD. The top plexiglass board represents the present land surface elevation at the place the photo was taken.

Figure 2. Instructor demonstrates the potential folding processes that created the folds in the outcrop behind him.

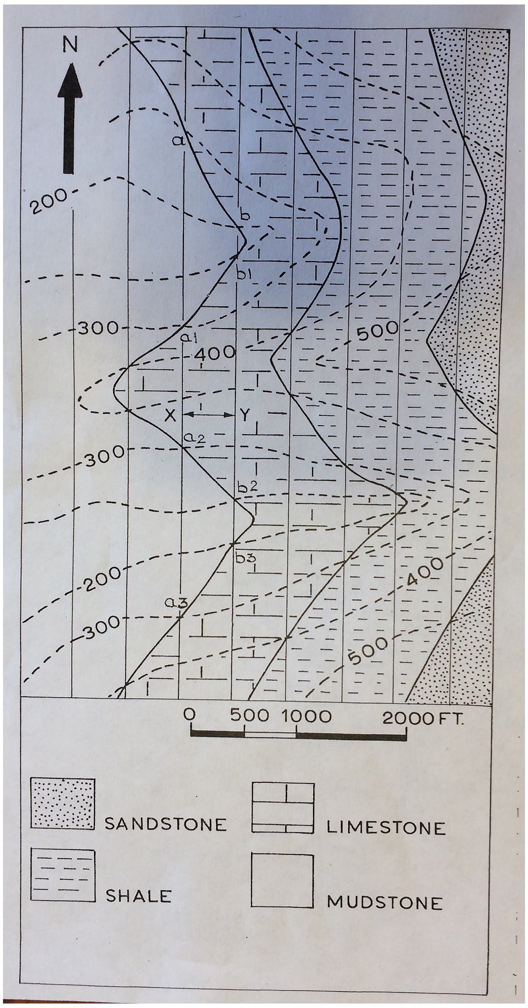

Figure 3. Map of homoclinal dipping beds used during the course, demonstrated in playdough in **Figure 4**.

Another course goal was to understand geologic structures and processes at and below Earth's surface. On the first field trip, students visited a site with a recumbent fold (see Figure 2). Here, the instructor used playdough to model two different ideas students had developed about how this sharp fold may have come about before moving closer to look for more fine-scale structures to support their thinking. Showing students the geologic process with playdough was intended to scaffold students' skill of mental animation.

As part of the course sequence, students went on three field trips. The first field trip took place early in the course and introduced field mapping techniques in the Badlands and Black Hills of South Dakota. In Fall 2019, the field trip took place at the end of the second week of the course. Over three days in the field, students honed their skill in the use of field instruments (compass, hand lens, sketching, etc.) and both topographic and geological map-reading, all of which had been introduced in lecture and lab before the field trip. The second field trip, at the end of the fifth week, was a one-day exploration of glacial landforms to reinforce topographic map-reading skills and illustrate concepts from geomorphology. At the end of week seven, students went on a one-day field trip to bedrock outcrop localities near the university with limited exposure between stops. Students used the data they collected about rock formation, orientation, elevation, and location to construct a variety of maps that challenged their increasing spatial thinking skills.

Student learning was assessed through normative formative and summative measures such as tests, quizzes, homework assignments, and lab exercises. Assessment used in this study included the two major exams given at the midpoint and end of the semester. Exams included content and skills that were and were not scaffolded by playdough models during instruction.

Data collection

During the Fall 2019 semester, two of the authors served as instructor (Tikoff) and teaching assistant (Barshi), while one author advised instructional design (Bateman). This team met weekly to determine in what ways playdough might be useful to the learning goals for the week. Tikoff, Barshi, and two other assistants enacted the plan in the course, documenting the playdough models and activities. Three of the authors (Tikoff, Barshi, and Bateman) attended the three-day class trip to South Dakota in Week 2 of the course where playdough was used as a major part of the learning plan.

Field trip data collection

During the three-day field trip to South Dakota in Week 2, the research team took ethnographic field notes, photographed activities, collected student formative assessment data, and conducted student surveys regarding the usefulness of playdough and other scaffolds such as instructor sketches on chart paper. At six stops on the field trip, students were asked to complete a formative assessment question related to the geology of the stop. Students also completed a set of survey questions (Appendix A) which asked for a ranking of the usefulness of each of a list of potential supports for learning, including playdough, on either a five- or a seven- point scale. Supports included instructor, teaching assistant, classmate explanation, playdough, and sketches. If they found playdough helpful, they were also asked to describe in what ways playdough was helpful.

In-class data collection

Students' perceptions of the usefulness of scaffolds were also captured during the middle and end of the semester in conjunction with exams. In a mid-term reflection, students were asked to rank how helpful they found the scaffolds, including playdough, and describe how they found playdough helpful in constructing of a cross-section from a flat line-representation, or map. An analogous survey was sent to students after the final exam to report on the usefulness of the same scaffolds throughout the course. During the final exam, students were asked to briefly reflect on the usefulness of playdough in answering a question that assessed their understanding of intrusive igneous bodies, which was similar to a real-world structure seen on the Black Hills field trip that was modeled with playdough in the field.

Analytic methods

Quantitative analysis

To test the usefulness of playdough, we assessed student understanding of the geological concepts taught using playdough at three points in the semester: the first field trip (South Dakota), the mid-term exam, and the final exam. The questions from the field trip worksheet were all short-answer prompts with options to sketch. Mid-term and final exams involved a variety of question types, including multiple choice, short answer, and interpretation of maps and diagrams with open-ended responses. A key for the field trip questions was created by the geology members of the team to allow any member to code answers for correctness. The mid-term and final were written and graded by the instructors of the course, and they were designed to evaluate student's mastery of the course material. All questions were normalized as percentage points to allow for comparisons across questions with various point values. Next, instructors identified which questions were conceptually related to the topics supported by playdough, and which questions covered structural geology or geological processes. From this process, three question categories were identified (Table 2): questions relevant to playdough that modeled geological *structure* (structure), questions relevant to playdough that modeled geological *processes* (process), and questions that were not relevant to playdough models (non-playdough).

Table 2. Descriptive statistics by question type at field trip and on exams. (Table view)

Question type	Field Trip Scores			Exam Scores		
	N	Mdn	SD	N	Mdn	SD
Structure	30	57.14	21.11	38	68.85	11.2
Process	30	41.67	18.89	38	49.58	20.99
Non-playdough	30	37.88	17.4	38	73.33	18.2

For the purposes of this study, student's accuracy scores on the three question categories were compared first within the field-trip surveys and then within their exams. Comparison between each category represents a quantitative approximation of the efficacy of playdough as an instructional tool for different geological concepts. The sample size of the current study (N = 38) is not sufficient, according to best practices, to calculate an unbiased Cronbach's alpha (Guadagnoli & Velicer, 1988; Yurdugül, 2008). Students' scores were not normally distributed, so Wilcoxon-signed rank tests (Tables 3 and 4) were used to compare student scores across the three types of questions (structure, process, and non-playdough) coded by the researchers. Our criterion for significance was a *p*-value less than or equal to 0.01.

Table 3. Wilcoxon comparison results on field trip. (Table view)

Comparison	W	z	r
Structure - Process	6***	3.39	0.62
Structure - Non-playdough	4***	4.06	0.74
Process - Non-playdough	12	1.46	0.27

** p < 0.01, *** p < 0.001 (alpha = 0.01).

Table 4. Wilcoxon comparison results on exams. (Table view)

Comparison	W	z	r
Structure - Process	6***	4.37	0.71
Structure - Non-playdough	14	2.05	0.33
Process - Non-playdough	3***	5.01	0.81

** p < 0.01, *** p < 0.001 (alpha = 0.01) .

Qualitative analysis

The research team approached analysis of the student responses to playdough usefulness in learning through a grounded theory approach (Glaser & Strauss, 2017). Three of the authors (Bateman, Ham, and Barshi) open-coded the responses for one field trip stop to generate codes grounded in the students' responses. Ideas were compared and discussed to develop an initial code book. Next, the three coders each visited a new section of the data set to test the code book from the initial coding. Because of the differential nature of expertise (science education, cognitive psychology, and geoscience respectively), answers were coded and discussed until agreement could be reached for each answer, modifying the code book as needed to better represent the student responses. The final codebook can be found in Table 5. Finally, each of the three coders assigned codes to all student responses and collectively discussed codes until agreement was reached.

Table 5. Playdough scaffolding codes. (Table view)

Theme	Code	Helps student to:	Example student responses

Theme	Code	Helps student to:	Example student responses
Supporting Academic Skills	Long Term Memory	Recall a structure or skill learned in a previous lesson or apply information learned from a previous lesson to a novel situation.	They allowed me to see what I was trying to visualize and furthered my inventory to call upon later (Final) I remembered the dome structure shown to us and imagined the layers removed to draw the contour lines. (Final Exam) I was able to draw an accurate depiction of how plutons would look when intruding between stratigraphic layers. (Final)
	Applying Skills	Use geological skills (i.e. drawing cross sections, creating structure-contours) either in tandem with playdough, or in novel situations later where playdough is not present.	Being able to create cross sections in front of our (sites) with playdough allowed me to understand the context of cross sections. (Field Trip) Yes, I imagined a 3 D model in cross-section to help make contours. [sketch of a cross section view] (Final)
	Evaluate Mental Hypothesis	Collect informal feedback on mental models or hypotheses of (incomplete) data or rock structures	I could somewhat imagine what this model looked like, but it helped confirm many of my theories, like any unconformities and vertical dikes (Midterm) They were helpful because they enabled me to test my 3 D knowledge of the structure, and then compare it to the answer. (Final)
Structures	Visualize/See/ Imagine	Generally envision the geology of a given area. (Playdough helped the student, but their response lacks detail to describe what it helps them see/visualize)	The playdough allowed me to visualize structures that I couldn't see clearly. (Field Trip) I see what's underneath the surface easier than a cross-section. (Mid-term)
	New Perspectives	Think about rock structures from views that are not currently possible (i.e. rotating large structures, changing angle of view)	Helped visualize where I am on the fault and helped visualize what the fault looked like from different views (Field Trip) Being able to rotate Badland stratigraphy allowed easier imagination of a vertical slice. (Field Trip) Being able to see the structures from angles that were impossible in real life, such as from beneath the surface, helped me better understand what was happening at any geological outcrop. (Final)
	Translating Between Representations	Translate between flat, line-representations and reality by providing an intermediary representation.	It helped me see the cross-section relative to the map (Mid-Term) This course has a lot of tough qualities about it, one of which is requiring a high level of 3 D thinking based from data and interpretations. The Play-Doh was very helpful in showing how models look and it made very hard to understand geologic structures, a lot more manageable. It was, visually, a lot easier to see how layers interacted with one-another when Play-Doh was used, and it really was a big help. (Final)

Theme	Code	Helps student to:	Example student responses
	Subsurface Structures	Mentally extend the visual field to parts of the rock structure that are beyond the current view such as underground or internal to a rock body.	The playdough helped me visualize and comprehend what was going on subsurface. (Field Trip) Explained how the layers were still here, but underneath the Minnelusa (Field Trip)
	Rock Relationships	Determine relationships between rock bodies such as way up indicators, stratigraphic layering, traces, and contacts of visible rock	The playdough was great for imagining the way the layers were in a monocline (Field Trip) The explanation of the contacts as well as the color-coded layers helped me better understand the stratigraphy. (Field Trip)
Process	What Led To Structures	Understand how changes over time led to the visible structures in the present	I was able to see how the rock could fold to make the structure. (Field Trip) The playdough model helped me to visualize the possibilities of how/why the older unit was at a higher elevation than the younger unit. (Field Trip) It was a good way of visualizing the steps of formation. (Field Trip)
	Connections Between Pieces	Take discrete parts of a landscape or system and connect their formation or deformation	[The playdough] made the large gap and the very high cliffs small enough to easily conceptualize a filled-in gap. (Field Trip) Using playdough helped me to mentally extend a plane, connecting the two faults and dipping toward the south. (Field Trip) The model helped show that layers extend all the way until they are eroded, so in the middle it should look the same as the outside. (Field Trip)

To enhance the validity of our study, we followed the triangulation approaches put forth by Stake (1995) with respect to case study research. We triangulated students' ideas about spatial skills with multiple measures, including student artifacts, student surveys, and observation field notes. We also used an interdisciplinary group of coders to analyze the data set. This triangulation of interdisciplinary investigators and theory created epistemic diversity and allowed the research team to discuss what each short response may mean, or if it meant anything of significance at all.

To bolster the value of our findings, we specifically solicited the students' impressions of how playdough was helpful to their understanding of geology. Their answers aided in our ability to capture the perceived relevance, which would be important for future acceptance of wider implementation and awareness of the role played by playdough in the construction of meaning. We present both the quantitative and qualitative data collected during the semester to inform our understanding of the usefulness of playdough in undergraduate geoscience courses.

Results

Our comparisons of students' performance on questions associated with different uses of playdough—to model a structure (such as an outcrop) or to model a process (such as how a fold formed)—indicate an overall reduction in playdough's usefulness to students as the course progressed. On the field trip, students performed significantly better on questions that were related to structural uses of playdough compared to either questions related to process uses or to questions tied to stops in which playdough was not used as a scaffold (non-playdough; Table 3). However, on exams later in the course, students scored significantly better on non-playdough and on structure questions as compared to process questions. There was no difference in performance on structure and non-playdough questions (Table 4).

To further investigate the impact the playdough had as a scaffold on students' learning of spatially dependent geological skills, we compiled the students' survey responses. In particular, we focused on whether students found the playdough helpful at the three measurement points during the study (South Dakota field trip, mid-term, final exam). The number of students who reported playdough as helpful decreased from 78% at the first stop of the South Dakota field trip to 44% in the final survey at the end of the course. To examine *how* students perceived playdough to be helpful to understand geology, we analyzed student responses to the survey components that asked about perceived utility in learning basic geologic structures, visualizing temporal and spatial processes, and supporting academic geologic skills. Students reported playdough to be useful in different ways at the three survey points within the course (the first field trip, the midterm exam, and the final exam).

Themes in usefulness of playdough

Students' responses of how playdough was useful fell into three main categories: supporting their understanding of geologic structures; geologic processes; and academic skills related to geologic tasks. Within these themes, students identified aspects of structure, process, and skills that were supported by the use of playdough models. Examples of student responses for each aspect/code can be found in Table 5.

Regarding geologic structures, students most frequently stated playdough helped in visualizing, seeing, or imagining structures (19.7% of all responses, $n = 44$) and identifying the relationships between rock structures (23.8%, $n = 53$). Other, less frequently noted ways playdough was felt to help learning were seeing geologic structures from new perspectives (6.3%, $n = 14$), translating between representations (10.8%, $n = 24$), and visualizing subsurface structures (9.4%, $n = 21$).

In addition to thinking about the geological structures, the playdough models were designed to support students in learning the geologic processes that led to visible structures, on both large spatial and temporal scales. Playdough was reported to be useful by students to see how different regions of rock had been connected in the past (e.g., sedimentary beds on either side of an erosional valley; 5.4%, $n = 12$), and how processes changed the landscape over time to reveal a structure (e.g., erosion exposing sequence of underlying sedimentary layers; 13.5%, $n = 30$).

Students attributed playdough to helping them develop general academic geologic practices including applying skills (drawing cross sections, creating structure contours; 2.7%, $n = 6$), evaluating mental hypotheses (3.1%, $n = 7$), and recalling information from their long-term memory (5.4%, $n = 12$). These skills were not specific to any particular geologic structure or process but applied across aspects of the course.

Changes to usefulness of playdough over time

In addition to gradual decline in usefulness of playdough models, the ways in which playdough models were included in the course to support geoscience learning changed over time. We note that on the first field trip to South Dakota, students were actively engaged with playdough models, but at the mid-term and final, students did not have the playdough visible to them. Instead, they were recalling learning that had occurred earlier in the course.

First, at the field trip in the beginning of the course, students reported playdough models supporting their understanding of *Rock Relationships* and both Process codes (*Connections Between Structures*, *What Led To Structures*) more than at later points in time (58.1% of coded responses at field trip 1, $n = 75$; 12.5% at mid-term, $n = 7$; 40.0% at final exam, $n = 13$; Table 6). Second, at the mid-term exam, students more often reported playdough supporting the structural concepts than process concepts, particularly *Subsurface Structures* and *Translating Between Representations* and the academic skills of *Applying Skills* and *Evaluating Mental Hypotheses* (19.3% of coded responses at field trip 1, $n = 25$; 70.3% at mid-term, $n = 14$; 27.2% at final exam, $n = 12$; Table 6). At the end of the course, students reported *Visualizing Structures*, *New Perspectives*, and the academic skill of *Long Term Memory* more than at other points in the course (22.5% of coded responses at field trip 1, $n = 29$; 12.5% at mid-term, $n = 3$; 54.3% at final exam, $n = 38$; Table 6). In the following section we describe these time points and provide examples of students' statements.

Table 6. Percentage of all codes assigned at each time point by code. (Table view)

		Field Trip 1 (N = 129)	Mid Term (N = 24)	Final (N = 70)	Total Codes (N = 223)
Structures	New Perspectives	6.20 (8)	0 (0)	8.57 (6)	6.28 (14)
	Visualizing	16.28 (21)	12.5 (3)	28.57 (20)	19.73 (44)
	Rock Relationships	31.78 (41)	29.17 (7)	7.14 (5)	23.77 (53)
	Subsurface Structures	11.63 (15)	12.5 (3)	4.29 (4)	9.42 (21)
	Translating Between Representations	6.20 (8)	29.17 (7)	12.86 (9)	10.76 (24)
Process	Connections Between Pieces	8.53 (11)	0 (0)	1.43 (1)	5.38 (12)
	What Led to Structures	17.83 (23)	0 (0)	10 (7)	13.45 (30)
Supporting Skills	Applying Skills	1.55 (2)	8.33 (2)	2.86 (2)	2.69 (6)
	Evaluating Mental Hypotheses	0 (0)	8.33 (2)	7.14 (5)	3.14 (7)
	Long Term Memory	0 (0)	0 (0)	17.14 (12)	5.38 (12)

Percentages for each category are listed first, with frequencies listed in parentheses. Some student responses were coded as supporting more than area.

Field trip 1

On the surveys from the South Dakota field trip, students reported the usefulness of playdough for understanding rock relationships and geologic processes more frequently than at the other two timepoints. "*Rock Relationships*" was coded when students indicated playdough supported their understanding of how rock bodies existed in relationship to one another. This included thinking about way-up indicators, stratigraphic layering patterns, and determining contacts and traces. For example, when first visiting the Badlands National Park, the instructors created a playdough model to explicitly teach the students how to find traces of contacts and faults in the surrounding landscape and practice sketching those features. Having the playdough model helped one student "understand where different contacts were. Showed [them] where to put [their] layers" during a field trip stop.

Students reported playdough models supported understanding of what happened in both connecting pieces and determining what processes led to which structures. At the start of the course, students visited the Little Elk Creek Trail in the Black Hills to examine a kilometer-scale monocline, a type of fold. Here, the class completed a hike, stopping along the way to collect strike and dip measurements of rock layer orientations and make observations of rock layers and rock types. Along the way, instructors created a playdough model piece by piece, using different colors of playdough to mimic the visible rock layers observed at each stop (Figure 1). Two sheets of plexiglass were used to show how the spatially separated rocks were connected underground. A key stop is nicknamed White Gate for the narrow passage of the Little Elk Creek and the trail between large outcrops of white limestone. One student stated, “It helped me connect the previous outcrops to White Gate and understand the contact between Pm [Pennsylvanian Minnelusa Formation] and Mp [Mississippian Pahasapa Limestone].”

Mid-term exam

At the mid-term, students reported understanding the subsurface structures, translating between representations of structures, using skills, and evaluating mental hypotheses more than at other points in the course. To do well on the mid-term exam, students needed to understand the geology beyond the visible structures on the surface. This requires reasoning about the inside of objects, by reasoning from what is visible on the objects’ surfaces. For larger scale geological problems, this reasoning requires translating information on a map to three dimensional structures in the world. Sketches, topographic maps, geologic maps, and cross-sections all require the translation between physical structures and the flat representation. For example, one student stated at the mid-term, “Initially I had a really hard time visualizing a 3 D model from a sketch, but the playdough models help me to better visualize a 2 D [sic] [1] sketch/map.”

The playdough activity was designed to provide students with a three-dimensional view not always possible in the field or classroom with other modeling tools such as block diagrams, computer simulations, or wooden blocks. One student noted that, “The playdough was great for seeing the cross section and it made it very easy to imagine the 3 D geometry.” Students stated that it was a particularly useful tool in situations where the playdough model was able to be sliced open to show the cross section they were trying to sketch. In the absence of playdough, students would have to mentally transform the three-dimensional structures to construct the cross-section. Instead, students could create the view themselves by cutting open the playdough model (Figure 5) and recording the view in a drawing.

The students’ mid-term survey responses also included indicators that the playdough helped students learn to construct geologic representations themselves, including drawing cross sections and determining dip direction, and evaluating their mental hypotheses. Students directly referenced being able to create a cross section, stating, “It helped me see the cross section relative to the map.” An example of a student recognizing playdough support for inference testing is this student referring to his theories about dip direction:

> I could somewhat imagine how this model looked but [the playdough] helped confirm many of my theories, like [if there were] any unconformities and vertical dikes.

End of course - final exam

At the completion of the course, structural-themed codes of *Visualizing*, *New Perspectives*, and *Long Term Memory* were more prevalent than at earlier time points (increasing 141% over their rate seen on the first responses from students). The code “*Visualize*” was applied when students spoke generally about seeing, imagining, or mentally picturing a structure without specifying which aspect of the structure was directly supported by the playdough. Students reported the playdough to be helpful in simplifying what they were seeing to make sense of the rock structure, with one stating, “the playdough helped simplify and clarify all the rock in a simplified version.” For another, “It taught me how to visualize in my head what Elkhorn Peak looked like with the different layers of geological units.” Students reported that the playdough models also provided them with “new perspectives” that were otherwise unachievable in the lab or on foot in the field. For example, top-down views are typically only visible with a drone or helicopter. As one student stated, “The playdough allows a complete 360-degree view of the structure where it is easier to look at the entire structure rather than the actual formation.” For other students, the new perspective served as a reminder to not always go with the first image of a feature, as is succinctly captured by this student: “The playdough helped the most in realizing how different a cross section could look based on perspective. Which also served as a good reminder about how beds might not be orientated how they look at first glance."

For the final exam, students found that they were able to recall a structure or skill from their long term memory and apply that to a new scenario. Students specifically described playdough as supporting their development of a "mental library". This term was used by the class instructors to help students think about creating mental models of geological structures which could be drawn upon during assessments and later in the field. For example, when asked to explain how playdough was helpful on the final exam, one student noted (referencing the model shown in Figure 5):

> While my answers might not be correct, I have a vivid memory, in my library, of the playdough model that was used when we got off the bus for Elkhorn Peak, that helped me break down and visualize the layers and how the intrusion affected the surrounding layers/topography better than anything else.

In another example (Figure 6), a different student specifically mentioned recalling the model of the Elkhorn Peak and the "red igneous body," the color of playdough seen in the model in Figure 5. For students, the creation of a playdough models "provided a good collection of three-dimensional models to reference when answering […] questions," as stated by another student at the final exam.

Discussion

Using classroom assessments to determine *if* playdough was helpful for students' understanding of geological concepts was inconclusive, but students' responses about *how* playdough was helpful supported the notion that it was a useful scaffold for learning to complete spatially dependent geologic tasks. In this discussion, we make three claims about the usefulness of playdough during this course. First, playdough scaffolded specific spatial skills in different ways. Second, playdough's usefulness waned during the course as geologic phenomena became increasingly complex. Finally, students found playdough very useful in the development of mental models during the learning process to be called upon for later problem solving during assessments. We conclude our discussion by reviewing the limitations and implications of this study.

Spatial skills and playdough scaffolding

A suite of spatial skills is crucial for the solving of complex geologic problems (Ormand et al., 2014) such as the types of challenges students face in final exams or more advanced geoscience courses. At least six potential spatial skills could be useful to geoscientists: disembedding, visually penetrative thinking, mental animation, mental rotation, perspective taking, and visually connecting spatially separated components. Although spatial demands of tasks within this course varied, the emic codes derived directly from students' responses revealed connections between the tasks, the scaffolding, and the spatial skills.

Playdough's usefulness in disembedding permeates many aspects of the course, starting with the first field trip stop where playdough models were used to help students understand the location of contacts and the difference between contacts and traces, a skill useful in all subsequent stops on the trip. Students needed to continue to filter out the "noise" in the geologic structures they were observing as the field trip and course continued (Reynolds, 2012). Using playdough, instructors were able to show how one can only see the trace of the contact on the rock's exposed surface, and that the plane of contact continues within the structure. For students, this was an initial connection with playdough useful for understanding rock relationships.

Two related skills relevant to the first field stop were perspective taking and mental rotation. Students had been asked to think about what the other side of the feature in front of them would look like. By viewing a playdough model of the feature, students who may have had difficulty imaging this could easily move the model around and see what likely would be on the other side by creating an external representation of the complex relationships (Johnson & Reynolds, 2012). This related to students seeing the usefulness of playdough for visualizing new perspectives, such as thinking about rock structures from currently unavailable views and the more general visualizing, in which students described playdough as helpful in “seeing” features present at the surface, like unconformities and contacts.

Throughout the course, students were asked to imagine what they might see beneath the surface, to employ the skill of visually penetrative thinking to use what they can see to infer what is inside the Earth. As students created cross sections, they had to think about the three-dimensional subsurface structures and visualize the appearance of a specific slice through the volume. Similar to three-dimensional block models used in other studies (Kali et al., 1997; Reynolds et al., 2005, 2006; Reynolds & Johnson, 2002), the playdough created a simplified, manipulable external representation of the geologic structure. The playdough model was able to simplify the visible structures and therefore make it easier for students to see how the rocks related to each other.

Scaffolding the understanding of geologic processes with playdough supported students’ mental animation and visually connecting skills. This was evident in the field trip stops at the Recumbent Fold (Figure 2) and White Gate (Figure 1) respectively. The ability to physically manipulate the playdough to show how a fold occurred created a way for students to see the process unfold instead of having to visualize this in their head with no prior experience of an analogous event to draw upon. Students reported that seeing the folding of the playdough supported them in making inferences about what led to specific structures. At White Gate, by successively building the playdough model to create a representation of the rocks along a hike that evolved as observations at each stop were included in the model, students were able to see the whole picture at once, in three dimensions, and use that information to make claims about the connections among the pieces, scaffolding their ability to connect spatially separated features.

In some cases, at both the mid-term and final exam, students noted that playdough was useful for the general task of visualizing, without specific mention of other spatial thinking tasks. Though students did not always elaborate on what this meant, some discussed how they could “see” previous models, or imagine the new structures, demonstrating spatial visualization skills (Newcombe & Shipley, 2015).

Newcombe (2012) posited that improving the geoscience learning requires both an improvement in individuals’ spatial skills and developing instructional materials which are fittingly paced for the learner, decrease the spatial demands, or are more “user friendly” (p. 85). Students in our study reported playdough modeling reduced their cognitive load, such as this student, at the end of the course:

> Sometimes when imagining multiple things it’s hard to keep track of them in your head. Playdough models act like a 3D physical representation that allows you to shift the focus of thought towards other things rather than the 3D object of shape.

This student was aware that just imaging flat, line-representations (maps, cross sections) as three dimensional figures was challenging and something that playdough helped eliminate from the forefront of their thinking. As the playdough is more user-friendly than complex modeling software, the playdough models draw on the pedagogical approaches advocated by Newcombe (2012) to support student geoscience learning.

Helpfulness decreases with complexity

Playdough was more helpful for reasoning about the basic processes and structures early in the course than complex ones and thus became less helpful as the course progressed. In the first stop of the first field trip, 78.9% ($N = 38$) students indicated playdough was helpful to at least some degree. At this location, students were introduced to the skill of identifying traces of contacts in the fairly flat lying layers near the Visitor’s Center of the Badlands National Park. However, at the next stop, students were asked to make connections between outcrops in a more complicated setting, both in terms of topography (gully) and geologic structures (faulted beds visible on either side of gully). Playdough was found to be less helpful to students there, with only 44% ($n = 16$) of students reporting playdough helpful. Students echoed this idea in responses at the end of the semester stating that playdough was helpful for "*visualizing* basic topics […] but not with more complex areas." One student articulated this clearly for learning about laccoliths on the final exam, related to a question about laccoliths in a more structurally complex setting than observed in the Black Hills:

> [It d]efinitely helped me in a lot of places. Not so much here, most of our laccolith models were very simple with no dips. For me, the playdough helps understand the very basic principles of what a laccolith is, [for] the more complex laccoliths I do better sketching them out.

Students likely were seeking a different scaffold for complicated geological concepts, specifically mentioning playdough as a "stepping stone to 3 D printed models" and requesting more wooden block models. However, the average class rating of usefulness of playdough at the end of course (4.08 of 5) was higher than that of the wooden block models (3.14 of 5) at the same timepoint. Therefore, we see playdough as useful for students to learn foundational topics and spatial skills then build on them with other learning approaches. Here, the usefulness of playdough as scaffold faded over time for some students, allowing students to move into a higher zone of proximal development and require different supports for learning more complex geoscience (Pea, 2004). The playdough models may have strengthened students' spatial skills and geoscience skills such that the scaffolds were no longer needed. If true, playdough would be an important addition to an instructor's toolkit because spatial skills have been found to predict success in geoscience (Liben & Titus, 2012), particularly for novices (Hambrick et al., 2012; Uttal & Cohen, 2012). Proper testing of this as a hypothesis will require a substantial study with a large sample and active control groups.

Supporting development of enduring mental models

Playdough appears to have supported the development of mental models that can be applied to reasoning about novel or complex variants of the basic structures or processes that students encountered throughout the course. We suggest students could potentially draw on these same models in their "mental library" in the future.

The creation of mental libraries was reported to be particularly effective for the final exam when students were asked questions about a laccolith, a structure seen at Elkhorn Peak in the Black Hills, about two months prior. Students who reported playdough to be helpful on the exam explained that they used their memories of seeing instructors create a playdough model of the intrusion that created Elkhorn Peak in front of the actual geology. One student recalled not only the laccolith causing doming of Elkhorn Peak, but the color of the playdough used in the model (see Figures 5 and 6), months after seeing the model in the field! Being able to recall previous visualizations aids geoscientists in solving novel problems throughout their coursework and careers (P. McNeal et al., 2018) by creating a larger "vocabulary" of patterns from which to recognize (Chase & Simon, 1973). Using playdough to scaffold the development of these mental libraries therefore can support students' progress in the field.

Figure 4. Playdough model and accompanying map of homoclinal dipping beds used during the course, the map of which is shown in Figure 3.

Figure 5. Elkhorn Peak, near the Black Hills, South Dakota, USA, with corresponding playdough model cross-section in foreground on first course field trip.

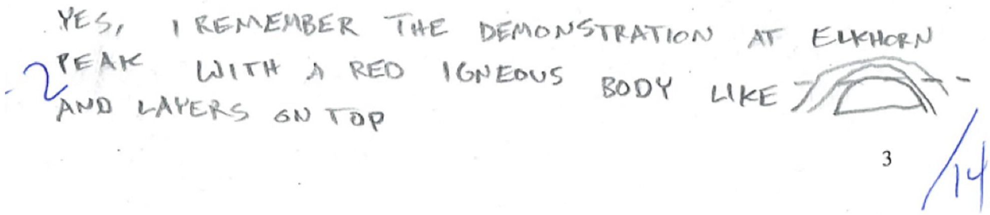

Figure 6. Student answer on final exam survey question about igneous intrusion similar to that at Elk Horn Peak, visible in Figure 5.

Limitations to the use of playdough

Playdough provided scaffolds to student understanding, but, like all models, has its limitations and ways in which it was less useful than another tool. Though students stated they enjoyed the "manipulability" of the playdough, they reported that construction of their own models was not as helpful to their conceptual understanding as viewing or manipulating models constructed by the instructors. Playdough was decreasingly reported as helpful compared to other types of structural models such as wooden block models or 3 D-printed versions as the course progressed. All models are imperfect; models can not represent all properties of their referent. Such limits are inherent and cannot be eliminated. In our design we explicitly acknowledged and called attention to the limits of the models. For example, at the White Gate stop (Figure 1), the playdough layers were simplified compared to the visible rock layers and not to scale. This was discussed to highlight the focus of the modeling: we simplified the layers in order to call attention to the connections between outcrops in different locations.

Finally, an obvious limit is playdough's material properties, which are unlike many rocks. The manipulability makes playdough well suited for demonstrating processes that have occurred over long time scales but not for illustrating rock mechanics. For example, fracturing is difficult to show in playdough; the modeling compound must be sliced rather than broken. Playdough is appropriate for representing geometry and some kinematics but not for rheology. Other familiar and affordable materials (Silly Putty, candy bars, yogurt, etc.) can replace playdough in demonstrating material properties and behaviors of rocks. Since this course's goals focused on geometry and kinematics, these were the focus of the intervention. Further work could examine the efficacy of these other simple, inexpensive scaffolds on student learning in more advanced geoscience courses.

Limitations of study

The modest sample size ($N = 38$) limits the generalizability of our quantitative results and does not allow us to assess the statistical reliability of our measures. We also did not explore how playdough might have interacted with students' prior experiences. However, we make a case for the robustness of our data set in the tradition of qualitative case study (Stake, 1995). Future investigations of the use of playdough models can build a data set large enough to allow comparisons by treatment group and analysis based on demographic information. Ideally, future work would also ask students about the perceived usefulness of playdough at additional time points during and after the course and for information that would allow critical design decisions, such as when student-built models and when instructor-built models were best, and for whom. We did not interview students; however, having them expand on their ideas may have provided more details about how they employed their experiences with playdough in course-related problem solving. Future studies may also choose to more deeply analyze the in-class interactions with playdough, rather than the focus on surveys and outcomes reported here. Finally, we did not assess student's spatial skills with a standard psychometric test, (e.g., of mental rotation), so how students' skills in decontextualized spatial reasoning might have changed is an open and important question to be addressed.

Implications

The development of spatial skills in geoscience is vital to novice geologists' development into experts (Uttal & Cohen, 2012). Although previous work has shown an improvement in spatial skills on quantitative metrics by taking a geoscience classroom course (Ormand et al., 2014) and field course (Hannula, 2019), we believe the use of scaffolding spatial skills' development through playdough models can improve on these outcomes, particularly in the field.

Playdough provided students with scaffolds for spatial skills in both the classroom and the field. We posit that curricula in early geoscience coursework should incorporate metacognitive strategies to help students self-regulate their use of scaffolds and allow for fading out the scaffolds over time (Pea, 2004). For some students in the study, playdough was reported to be less useful in the later portion of the course, as they mastered the spatial-dependent course goals of creating cross sections and interpreting topographic maps, but the playdough models were still being presented and used with all students. Reflecting on their own learning needs and deciding what to do about their needs is something students should and can be taught (Bransford et al., 2000). Metacognitive skills are valued in the geosciences (see Mogk & Goodwin, 2012; Petcovic & Libarkin, 2007 for overviews) but further empirical evidence on their effectiveness in undergraduate geoscience courses is needed (Lukes et al., 2021; McNeal et al., 2018).

Playdough has some important affordances for field geoscience instruction. Playdough was reported to be more useful in the field than at exam times. Employing this scaffold to make the connections between structure and process can help students navigate the difficult tasks involved in comprehending the larger temporal-spatial scales in which geoscience occurs. Playdough can be used in the field to support mental animation, by showing the possible processes that led to a structure, or erosional patterns of exposure and landscape. Playdough also allowed students in the field to rotate structures and cut into them to support development of their visual penetrative thinking. This allows the instructor to be responsive to the needs of the students in front of them quickly, easily, and inexpensively. Although other models, such as augmented reality sandboxes (Woods et al., 2016) and 3 D printing (Carbonell Carrera et al., 2017), could be used to support learning, these are not easily transported to the field for use with students when they encounter a spatially challenging concept. Using a simple, familiar, and inexpensive tool in the place of more complex modeling software which requires knowledge of technology and programming language also affords geoscience opportunities to be more inclusive of students who do not come to geoscience courses with that knowledge.

Conclusion

Playdough models can provide a scaffold for the learning of geoscientific spatial skills in mid-level geology classrooms and related field experiences. These modeling tools are well suited for geoscience due to their portability, inexpensive cost, and familiarity to students. Our findings support playdough model use with undergraduate students who experience these models as useful in both the field and classroom, so students will be likely to engage with them. Student surveys showed that though the usefulness of playdough models waned during the semester, the impacts on students' spatial skills and "mental libraries" makes playdough models productive for learning basic geologic phenomena. Playdough models may be particularly effective when modeling the geologically slow process of folding or when students need small, manipulable models of large spatial structures. We suggest that further research employ larger sample sizes and include standard psychometric tests of spatial skills to better understand the impact of playdough models on the spatial skills necessary for success in geoscience courses that prepare novices for professional practice.

Notes

Here, the student refers to a sketch/map as two-dimensional despite the information they hold for three-dimensional space. We refer to these in our work as representations of three-dimensional objects or forms, or flat, line-representations.

Funding

This work was supported by the National Science Foundation under Grant NSF DUE 1839705 and NSF SL-CN 1640800.

References

Alibali, M. W., Spencer, R. C., Knox, L., & Kita, S. (2011). Spontaneous gestures influence strategy choices in problem solving. *Psychological Science*, *22*(9), 1138–1144.

Allison, G., & Zelikow, P. (1999). *The essence of decision making: Explaining the Cuban Missle crisis*. Pearson.

Atit, K., Gagnier, K., & Shipley, T. F. (2015). Student gestures aid penetrative thinking. *Journal of Geoscience Education*, *63*(1), 66–72.

Atit, K., Shipley, T. F., & Tikoff, B. (2013, May). Twisting space: Are rigid and non-rigid mental transformations separate spatial skills? *Cognitive Processing*, *14*(2), 163–173.

Bitting, K. S., Teasdale, R., & Ryker, K. (2017). Applying the geoscience education research strength of evidence pyramid: Developing a rubric to characterize existing geoscience teaching assistant training studies. *Journal of Geoscience Education*, *65*(4), 519–530.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school*. National Academy Press.

Carbonell Carrera, C., Avarvarei, B. V., Chelariu, E. L., Draghia, L., & Avarvarei, S. C. (2017). Map-reading skill development with 3D technologies. *Journal of Geography*, *116*(5), 197–205.

Chase, W. G., & Simon, H. A. (1973). Perception in chess. *Cognitive Psychology*, *4*(1), 55–81.

Cobb, P. (1994). Constructivism in mathematics and science education. *Educational Researcher*, *23*(7), 4–4.

Denzin, N. (1978). *Toward a sociology of education*. Taylor & Francis.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology*, *42*(6), 1259–1268.

Gilbert, J. K., & Osborne, R. J. (1980). The use of models in science and science teaching. *European Journal of Science Education*, *2*(1), 3–13.

Glaser, B. G., & Strauss, A. L. (2017). *Discovery of grounded theory: Strategies for qualitative research*. Routledge.

Gold, A. U., Pendergast, P. M., Ormand, C. J., Budd, D. A., & Mueller, K. J. (2018). Improving spatial thinking skills among undergraduate geology students through short online training exercises. *International Journal of Science Education*, *40*(18), 2205–2225.

Guadagnoli, E., & Velicer, W. F. (1988). Relation of sample size to the stability of component patterns. *Psychological Bulletin*, *103*(2), 265–275.

Guba, E. G., & Lincoln, Y. S. (1994). Competing paradigms in qualitative research. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of qualitative research* (pp. 105–117). Sage.

Hambrick, D. Z., Libarkin, J. C., Petcovic, H. L., Baker, K. M., Elkins, J., Callahan, C. N., Turner, S. P., Rench, T. A., & LaDue, N. D. (2012). A test of the circumvention-of-limits hypothesis in scientific problem solving: The case of geological bedrock mapping. *Journal of Experimental Psychology. General*, *141*(3), 397–403.

Hannula, K. A. (2019). Do geology field courses improve penetrative thinking? *Journal of Geoscience Education*, *67*(2), 143–160.

Hegarty, M., & Sims, V. K. (1994). Individual differences in mental animation during mechanical reasoning. *Memory & Cognition*, *22*(4), 411–430.

Hepworth, K., Ivey, C. E., Canon, C., & Holmes, H. A. (2020). Embedding online, design-focused data visualization instruction in an upper-division undergraduate atmospheric science course. *Journal of Geoscience Education*, *68*(2), 168–183.

Herrera, J. S., & Riggs, E. M. (2013). Relating gestures and speech: An analysis of students' conceptions about geological sedimentary processes. *International Journal of Science Education*, *35*(12), 1979–2003.

Horowitz, S. S., & Schultz, P. H. (2014). Printing space: Using 3D printing of digital terrain models in geosciences education and research. *Journal of Geoscience Education*, *62*(1), 138–145.

Ishikawa, T., & Kastens, K. A. (2005). Why some students have trouble with maps and other spatial representations. *Journal of Geoscience Education*, *53*(2), 184–197.

Jaeger, A. J., Shipley, T. F., & Reynolds, S. J. (2017). The roles of working memory and cognitive load in geoscience learning. *Journal of Geoscience Education*, *65*(4), 506–518.

Jee, B. D., Uttal, D. H., Gentner, D., Manduca, C., Shipley, T. F., Tikoff, B., Ormand, C., & Sageman, B. (2010). Commentary: Analogical thinking in geoscience education. *Journal of Geoscience Education*, *58*(1), 2–13.

Johnson, J. K., & Reynolds, S. J. (2005). Concept sketches—Using student-and instructor-generated, annotated sketches for learning, teaching, and assessment in geology courses. *Journal of Geoscience Education*, *53*(1), 85–95.

Kali, Y., & Orion, N. (1996). Spatial abilities of high school students in the perception of geologic structures. *Journal of Research in Science Teaching*, *33*(4), 369–391.

Kali, Y., Orion, N., & Mazor, E. (1997). Software for assisting high-school students in the spatial perception of geological structures. *Journal of Geoscience Education*, *45*(1), 10–21.

Klippel, A., Zhao, J., Jackson, K. L., La Femina, P., Stubbs, C., Wetzel, R., Blair, J., Wallgrün, J. O., & Oprean, D. (2019). Transforming earth science education through immersive experiences: Delivering on a long held promise. *Journal of Educational Computing Research*, *57*(7), 1745–1771.

Libarkin, J. C., & Brick, C. (2002). Research methodologies in science education: Visualization and the geosciences. *Journal of Geoscience Education*, *50*(4), 449–455.

Liben, L. S., & Titus, S. J. (2012). The importance of spatial thinking for geoscience education: Insights from the crossroads of geoscience and cognitive science. *Geological Society of America Special Papers, 486*, 51–70.

Lin, L. F., Hsu, Y. S., & Yeh, Y. F. (2012). The role of computer simulation in an inquiry-based learning environment: Reconstructing geological events as geologists. *Journal of Science Education and Technology*, *21*(3), 370–383.

Lukes, L. A., Jones, J. P., & McConnell, D. A. (2021). Self-regulated learning: Overview and potential future directions in geoscience. *Journal of Geoscience Education*, *69*(1), 14–26.

Manduca, C. A., & Kastens, K. (2012). Mapping the domain of spatial thinking in the geosciences. *Geological Society of America Special Paper, 486*, 45–49.

McConnell, D. A., Chapman, L., Czajka, C. D., Jones, J. P., Ryker, K. D., & Wiggen, J. (2017). Instructional utility and learning efficacy of common active learning strategies. *Journal of Geoscience Education*, *65*(4), 604–625.

McNeal, P., Ellis, T., & Petcovic, H. (2018). Investigating the foundations of spatial thinking in meteorology. *Journal of Geoscience Education*, *66*(3), 246–257.

McNeal, K. S., Van der Hoeven, Kraft, K., Nagy-Shadman, E., Beck, M., & Jones, J. (2018). Research on geoscience students' self-regulated learning, metacognition, and affect. In K. St. John (Ed.), *Community framework for geoscience education research* (pp.114–1230).National Association of Geoscience Teachers.

Mogk, D. W., & Goodwin, C. (2012). Learning in the field: Synthesis of research on thinking and learning in the geosciences. *Geological Society of America Special Papers, 486*, 131–163.

Montello, D. R. (2010). You are where? The function and frustration of You-Are-Here (YAH) maps. *Spatial Cognition & Computation*, *10*(2–3), 94–104.

Newcombe, N. S. (2012). Two ways to help students with spatial thinking in geoscience. *Geological Society of America Special Papers, 486*, 85–86.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: New typology, new assessments. In J. S. Gero (Ed.), *Studying visual and spatial reasoning for design creativity* (pp. 179–192). Springer.

Ormand, C. J., Manduca, C., Shipley, T. F., Tikoff, B., Harwood, C. L., Atit, K., & Boone, A. P. (2014). Evaluating geoscience students' spatial thinking skills in a multi-institutional classroom study. *Journal of Geoscience Education*, *62*(1), 146–154.

Palincsar, A. S. (1998). Keeping the metaphor of scaffolding fresh-a response to C. Addison Stone's "The metaphor of scaffolding: Its utility for the field of learning disabilities". *Journal of Learning Disabilities*, *31*(4), 370–373.

Pallant, A., & Lee, H. S. (2017). Teaching sustainability through system dynamics: Exploring stocks and flows embedded in dynamic computer models of an agricultural land management system. *Journal of Geoscience Education*, *65*(2), 146–157.

Pea, R. D. (2004). The social and technological dimensions of scaffolding and related theoretical concepts for learning, education, and human activity. *Journal of the Learning Sciences*, *13*(3), 423–451.

Petcovic, H. L., & Libarkin, J. C. (2007). Research in science education: The expert-novice continuum. *Journal of Geoscience Education*, *55*(4), 333–339.

Ping, R., & Goldin-Meadow, S. (2010). Gesturing saves cognitive resources when talking about nonpresent objects. *Cognitive Science*, *34*(4), 602–619.

Plummer, J. D., Bower, C. A., & Liben, L. S. (2016). The role of perspective taking in how children connect reference frames when explaining astronomical phenomena. *International Journal of Science Education*, *38*(3), 345–365.

Resnick, I., & Shipley, T. F. (2013). Breaking new ground in the mind: An initial study of mental brittle transformation and mental rigid rotation in science experts. *Cognitive Processing*, *14*(2)May), 143–152.

Reynolds, S. J. (2012). Some important aspects of spatial cognition in field geology. *Earth & Mind II: Synthesis of Research on Thinking and Learning in the Geosciences*. *Geological Society of America Special Publication*, *486*, 75–78.

Reynolds, S., & Johnson, J. K. (2002). GeoBlocks 3D - Interactive 3D geologic blocks. *Journal of the Virtual Explorer*, *9*, 38–39.

Reynolds, S. J., Johnson, J. K., Piburn, M. D., Leedy, D. E., Coyan, J. A., & Busch, M. M. (2005). Visualization in undergraduate geology courses. In J. K. Gilbert (Ed.), *Visualization in science education. Models and modeling in science education* (Vol. 1, pp. 253–266). Springer.

Reynolds, S. J., Piburn, M. D., Leedy, D. E., McAuliffe, C. M., Birk, J. P., & Johnson, J. K. (2006). The Hidden Earth—Interactive, computer-based modules for geoscience learning. *Geological Society of America Special Papers, 413*, 157–170.

Rideout, V., & Katz, V. S. (2016). Opportunity for all? Technology and learning in lower-income families. In *The Families and Media Project, Joan Ganz Cooney Center at Sesame Workshop*. https://joanganzcooneycenter.org/wp-content/uploads/2016/01/jgcc_opportunityforall.pdf

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context*. Oxford University Press.

St. John, K., & McNeal, K. S. (2017). The strength of evidence pyramid: One approach for characterizing the strength of evidence of geoscience education research (GER) community claims. *Journal of Geoscience Education*, *65*(4), 363–372.

Stake, R. E. (1995). *The art of case study research*. Sage.

Taber, K. S. (2014). Methodological issues in science education research: A perspective from the philosophy of science. In M. Matthews (Eds.), *International handbook of research in history, philosophy and science teaching* (pp. 1839–1893). Springer.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: When, why, and how? In B. H. Ross (Ed.), *The psychology of learning and motivation* (pp. 147–181). Elsevier Academic Press.

Van Boening, A. M., & Riggs, E. M. (2020). Geologic gestures: A new classification for embodied cognition in geology. *Journal of Geoscience Education*, *68*(1), 49–64.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *17*(2), 89–100.

Woods, T. L., Reed, S., Hsi, S., Woods, J. A., & Woods, M. R. (2016). Pilot study using the augmented reality sandbox to teach topographic maps and surficial processes in introductory geology labs. *Journal of Geoscience Education*, *64*(3), 199–214.

Yin, R. K. (2009). *Case study research: Design and methods* (Vol. 5). Sage.

Yurdugül, H. (2008). Minimum sample size for Cronbach's coefficient alpha: A Monte-Carlo study. *Hacettepe Üniversitesi Eğitim Fakültesi Dergisi (H.U. Journal of Education)*, *35*, 397–405.