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Spatial skill predicts success on sequence stratigraphic interpretation

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ABSTRACT

Sequence stratigraphic interpretation and three-dimensional spatial and spatiotemporal skills are considered important for the petroleum industry. However, little is known about the relationship between the two. This study begins to fill this gap by testing whether spatial skills predict success on a sequence stratigraphic interpretation task. Students in this study (*N* = 78) were enrolled in undergraduate or graduate stratigraphy-focused courses at three U.S. state universities. Students completed (1) a sequence stratigraphic interpretation task with a sequence stratigraphic diagram and Wheeler diagram and (2) two spatial skills tests. Findings of simple linear regressions show that both disembedding (extracting or finding a pattern among other features, which is typically assessed by the hidden-figures test) and mental folding and unfolding (as assessed by the surface development test) are predictive of student success on the full sequence stratigraphic interpretation task. A nested regression, entering mental folding as the initial variable and disembedding as the secondary variable, showed that mental folding and unfolding accounted for almost all of the variance accounted for by disembedding in the simple regression. This may reflect the need to employ disembedding for the test of mental folding. Because the test of disembedding and the test of mental folding and unfolding were correlated, the distinct role of disembedding in stratigraphy remains unclear. However, the results clearly show that mental folding and unfolding is related to student success in sequence stratigraphic interpretation. Future studies should characterize how students utilize these skills, try to determine the causal direction of this effect, and identify good practices for supporting students in the classroom.

INTRODUCTION

A recent effort to define the most important skills for the geoscience workforce highlighted two-dimensional (2-D) and three-dimensional (3-D) spatial problem-solving skills (Summa et al., 2017). Two reports by employers and academics agree that spatial skills are important for student success in the geosciences: (1) A transdisciplinary conference of cognitive scientists, geoscience educators, and industry geoscientists explored the importance of spatial thinking for geologic interpretation (Krantz et al., 2016a), and (2) the Community Framework for Geoscience Education Research, a set of community-endorsed grand challenges for research, identified spatial and temporal reasoning as a priority for the geoscience education research (GER) community (St. John, 2018).

Evidence from psychology and STEM (science, technology, engineering, and math) education research underscores the importance of spatial thinking for success in STEM fields generally (Wai et al., 2009; Lubinski, 2010; Uttal and Cohen, 2012; Newcombe and Shipley, 2015; Stieff and Uttal, 2015) and the geosciences specifically (Kastens and Ishikawa, 2006; Shipley et al., 2013; Ormand et al., 2014). Notably, the literature shows that spatial thinking is malleable (Uttal et al., 2013) and no individual spatial skill predicts a student's overall success in geosciences courses (Ormand et al., 2014). To understand how spatial thinking plays a role in geoscience education, it is essential to understand which skills are associated with various geologic tasks.

A few studies have explored the role of spatial thinking in sedimentology and stratigraphy, but none has focused specifically on sequence stratigraphy. Recent investigations document cognitive workflows and uncertainty for interpreting subsurface geology (Bond et al., 2010, 2012; Alcalde et al., 2017), but none has identified the spatial skill needed for those interpretations. Herrera and Riggs (2013a) suggested that sequence stratigraphy is difficult for students due to the combination of temporal and spatial thinking. For example, interpreting changes in relative sea level requires one to update movement in time and space. Additionally, disembedding (extracting or finding a pattern among other features) may be necessary for upper-level sequence stratigraphic tasks such as seismic interpretations (Table 1) (Kastens and Ishikawa, 2006). However, no empirical evidence has confirmed this relationship. This study is the first attempt to address this gap by assessing the relationship between spatial skills and sequence stratigraphic interpretation. We aimed to assess the relationship between two spatial skills (e.g., disembedding and mental folding and unfolding) and students' scores on a sequence stratigraphic interpretation task, which included reasoning using both a sequence stratigraphic diagram and Wheeler diagram.

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TABLE 1. DEFINITIONS AND USE OF SPATIAL SKILLS

Spatial skill	Definition	Sequence stratigraphic use
Disembedding	To isolate a single image (line or shape) from a complex background (Newcombe and Shipley, 2015).	Isolating packages or layers representative of systems tracts or surfaces (e.g., subaerial unconformities).
Mental folding or unfolding	Mentally fold a shape into a new object or mentally unfold an already folded object into its original shape.	Ability to unfold the naturally draped layers of the sequence stratigraphic diagram to correlate to the horizontal time layers of the Wheeler diagram.

The Spatial Dimensions of Sequence Stratigraphy

Sequence stratigraphy has proven invaluable to the petroleum industry since the pioneering work by Sloss et al. (1949) and continues to be a highly sought-after interpretation skill (Heath, 2000). The use of 2-D seismic images and chronostratigraphic diagrams is common within sequence stratigraphy (Xu et al., 2020). In academia, undergraduate and graduate student training includes sequence stratigraphic diagrams and Wheeler diagrams (Fig. 1). Sequence stratigraphic diagrams are simplified images of sequences that reflect the geometries of a seismic profile (Fig. 1B). Wheeler diagrams, originating from the work of Henry Wheeler (1958, 1964), take the depositional layers of the sequence stratigraphic diagram or seismic profile and transform them into an approximation of a time versus distance graph, with the *y*-axis representing the temporal dimension of deposition (Fig. 1A). In a recent study, Xu et al. (2020) suggested that adding along-strike use of these diagrams could facilitate 3-D sequence stratigraphic interpretations.

Employee 3-D spatial and spatiotemporal skills are important to both academia and industry equally (Summa et al., 2017). At a 2013 American Association of Petroleum Geologists Hedberg Conference in Reno, Nevada (USA), petroleum industry leaders, cognitive scientists, and geoscience educators gathered to synthesize and explore the 3-D and spatiotemporal skills associated with a range of geology tasks. The proceedings (Krantz et al., 2016b) set out key objectives that include prioritizing interdisciplinary work to understand subsurface geology and spatial thinking relationships. Stratigraphy (McGinnis et al., 2016) and seismic interpretation (Boult et al., 2016; Yielding and Freeman, 2016) were among the areas considered in reports from this conference; none of the workgroups specifically considered sequence stratigraphic interpretation.

Recent studies have begun to explore student understanding of sequence stratigraphy. Both upper-level undergraduates and graduate students struggle with the underpinning concepts associated with sequence stratigraphy (e.g., base level, relative sea level, eustasy, and accommodation) (Herrera and Riggs, 2013a). Additionally, Herrera and Riggs (2013b) noted that students use more frequent and complex gestures when discussing these topics, suggesting they are more cognitively challenging. Despite literature demonstrating that spatial thinking is vital for sequence stratigraphy interpretation (Kreager, 2021; Herrera and Riggs, 2013a, 2013b; Xu et al., 2020), no empirical data exist to support the hypothesized links between spatial thinking and sequence stratigraphy.

What Are Spatial Thinking Skills?

Spatial thinking is one's ability to mentally process the world in such a way as to navigate it and identify and manipulate shapes, locations, and relationships amongst objects (Newcombe and Shipley, 2015). The concept of spatial thinking has roots in the cognitive sciences (e.g., Shepard and Metzler, 1971; Cooper and Shepard, 1973; Baddeley and Hitch, 1974), neuroscience (Asselen et al., 2006; Fukushima, 1980; Amorapanth et al., 2010), and research on general intelligence (Carroll, 1993; Horn, 1972; Hakstian and Cattell, 1974; Ekstrom et al., 1979). More recently, new frameworks distinguish the types of spatial skills associated with various cognitive tasks. For example, Chatterjee (2008) presented a general framework classifying two types of spatial reasoning about objects: (1) intrinsic skills (reasoning applied to a single object) versus extrinsic skills (reasoning applied to two or more objects), and (2) static skills (reasoning applied to an object that is not moving or changing) versus dynamic skills (reasoning applied to an object that is moving or changing). Uttal et al. (2013) utilized this literature and the emerging 2 × 2 matrix of intrinsic and extrinsic versus static and dynamic skills to code interventions in a meta-analysis that evaluated the malleability of spatial skills. They concluded that spatial skills are malleable and trainable. Building upon this literature, Newcombe and Shipley (2015) proposed a typology of spatial skills that classifies 11 types of spatial skills within the 2 × 2 matrix. Geoscience education researchers utilize these frameworks and typologies to explore the relevant spatial skills for geoscience tasks.

Which Spatial Skills Are Important for the Geosciences?

Early work addressing spatial thinking in the geosciences distinguished between the three ways geoscientists use spatial thinking: (1) describing and interpreting objects (e.g., using the shape of an object to identify it), (2) comprehending spatial properties and processes (e.g., creating a 3-D mental image from 1-D and 2-D data), and (3) metaphorical usages of spatial thinking (e.g., using space as a proxy for time) (Kastens and Ishikawa, 2006). In addition to these categories, Kastens and Ishikawa (2006) provided theoretical linkages between spatial thinking and the geosciences, laying the groundwork for empirical testing of which spatial skills were important for which tasks.

Empirical research in the geosciences demonstrates that various spatial skills are integral to geologic tasks (Jee et al., 2013; Ormand et al., 2014;

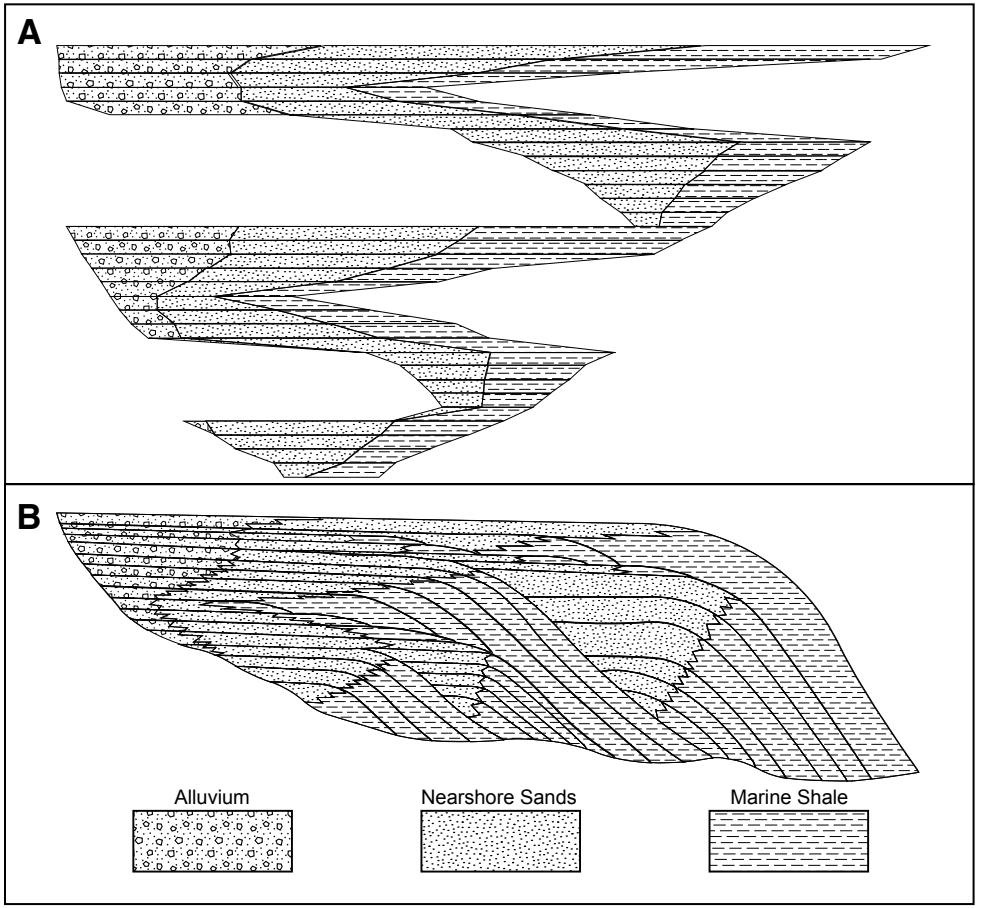

Figure 1. Idealized sequence created for the use of this study. (A) Example of a Wheeler diagram. (B) Example of a sequence stratigraphic diagram. Diagram A expands the naturally draped layers of diagram B into time-versus-distance layers.

Resnick and Shipley, 2013; Atit et al., 2015; McNeal et al., 2019; Hannula, 2019). Importantly, there is no single spatial skill key to overall success in the geosciences (Ormand et al., 2014). Most GER studies focus on three spatial skills measured by cognitive tests: mental rotations (e.g., Purdue visualization of rotations test [Guay, 1976] and Vandenberg and Kuse mental rotations test [Vandenberg and Kuse, 1978]), disembedding (e.g., hidden figures test [Ekstrom et al., 1976a]), and penetrative thinking (e.g., planes of reference test [Titus and Horsman, 2009] and geologic block cross-section test [Ormand et al., 2014]). Less frequently studied are two additional cognitive skills associated with object transformation (e.g., the mental brittle-deformation test) (Resnick and Shipley, 2013) and field dependence (e.g., water-level test) (Hannula, 2019).

Of the spatial skills discussed above, disembedding is understudied but applies to a variety of geoscience tasks. Kastens and Ishikawa (2006) proposed that disembedding is an essential skill for map reading (e.g., interpreting contour lines) and interpreting seismic images. McNeal et al. (2019) found that the disembedding skill was important for forecasting with meteorology maps for low- and high-knowledge participants and, when combined with domain knowledge, was predictive of scores on meteorological tasks. Meteorology involves interpretation of 3-D dynamic processes represented by 2-D static diagrams and maps, requiring similar cognitive processes as those used with sequence stratigraphy.

The Sequence Stratigraphic Spatial Training (SSST) framework outlines the hypothesized links between spatial skills and sequence stratigraphic tasks at all physical scales of interpretations (Kreager, 2021). Within the SSST framework, disembedding and mental folding and unfolding skills are identified as critical for students' interpretation of sequence stratigraphic and Wheeler diagrams (Table 1). For example, students need to isolate sediment packages and identify boundaries when interpreting both seismic profiles and sequence stratigraphic diagrams; this skill would require disembedding. In interpreting sequence stratigraphic and Wheeler diagrams, students need to mentally unfold the naturally draped layers of a sequence stratigraphic diagram.

The research questions guiding this study are: (1) Does spatial visualization predict sequence stratigraphic diagram interpretation? and (2) Which spatial visualization skills predict sequence stratigraphic diagram interpretation? This investigation focuses on disembedding and mental folding or unfolding because they are aligned with the cognitive processes associated with the task (Kreager, 2021).

METHODS

To test the research questions, we administered an assessment requiring students to complete a sequence stratigraphic diagram and a corresponding Wheeler diagram interpretation, a sequence stratigraphic concept knowledge and experience survey, and two cognitive tests—hidden figures and surface development. Students spent ~50 min

TABLE 2. DEMOGRAPHICS BY UNIVERSITY

University	*n*	Sex		Ethnicity					
		Male	Female	White	Black	Latino/Hispanic	Asian	Multiple ethnicities	Prefer not to answer
University 1	3	2 (66.7%)	1 (33.3%)	3 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
University 2	11	5 (45.5%)	6 (54.5%)	7 (63.6%)	0 (0%)	1 (9.1%)	0 (0%)	3 (27.3%)	0 (0%)
University 3	64	38 (59.4%)	26 (40.6%)	35 (54.7%)	1 (1.6%)	15 (23.4%)	5 (7.8%)	6 (9.4%)	2 (3.1%)
Total	78	45 (57.7%)	33 (42.3%)	45 (57.7%)	1 (1.3%)	16 (20.5%)	5 (6.4%)	9 (11.5%)	2 (2.6%)

in class performing these tasks after receiving instruction on sequence stratigraphy and Wheeler diagram interpretation from their regular instructor.

Population

Three faculty members from U.S. universities invited the lead author into their courses to collect data for this study. University 1 was a large, research-focused midwestern U.S. university (R2 in the Carnegie Classification of Institutions of Higher Education, http://carnegieclassifications.iu.edu/index.php), with a total student enrollment of >16,000 students, of which 51.2% were female and 51% were White. University 2 was a large R2 southwestern U.S. Hispanic-Serving Institution (HSI) with >14,000 students who were 56.6% female and 57.8% Hispanic. University 3 was a large, very high research activity (R1) southwestern U.S. university with >69,000 students who were 48.6% female and 54.7% White.

This study recruited participants from three courses covering stratigraphy and sedimentology topics. Two courses were 300- or 400-level undergraduate courses for majors, and one course was a 600-level graduate course. The U.S. higher-education system commonly uses course levels 100–400 to denote undergraduate courses and 500+ for graduate courses. The 300- and 400-level courses in this study consisted primarily of students in their third or fourth year at university and majoring in the field. The 600-level graduate course was available to both master's and Ph.D. students at any point in their graduate degree but consisted of only master's students in this study.

For the graduate course, three master's-level students consented to participate, and all students identified as White, with two identifying as male and one as female (Table 2). For the 400-level undergraduate-only course, 11 students consented, 54.5% of whom identified as female, and self-identified as White (63.6%), multiple ethnicities (27.3%), and Latino/Hispanic (9.1%) (Table 2). The 300-level undergraduate-only course included 64 consenting students over two semesters. A majority of students identified as male (59.4%) and White (54.7%), and 15 students (23.4%) identified as Latino/Hispanic, six (9.4%) as having multiple ethnicities, five as Asian (7.8%), and one as Black (1.6%), and two (2.6%) preferred not to provide an ethnicity. All students enrolled in the courses completed the research study tasks regardless of consent, and no incentives were offered. Data from only those students who consented were included in this study.

Instruments

Sequence Stratigraphic Task

The sequence stratigraphic task included one original sequence stratigraphic diagram and a corresponding Wheeler diagram (Fig. S1[1]). The diagrams assessed students' interpretation skill after learning about sequence stratigraphic concepts and diagrams and Wheeler diagrams. The sequence stratigraphic diagrams and Wheeler diagrams represented idealized fictional sequences modeled after, but not identical to, a commonly used activity by Jerry Baum (http://www.sepmstrata.org/Terminology.aspx?id=chronostratigraphy). The task had 10 questions, each asking students to identify stratigraphic sequence features with model-specific jargon removed. For example, a question asked them to identify layers representing low sea levels, probing their understanding of a lowstand systems tract package of bedding without using that terminology. The task was reviewed, edited, and approved by two authors (Powell and Hampton) with expertise in sedimentology, sequence stratigraphy, and basin analysis. Readability was evaluated by having three graduate students who recently completed a sequence stratigraphic course complete the task. Questions that were misunderstood were reworded to ensure participants understood the questions.

The task design allowed students to work untimed at their own pace. Authors Kreager and Powell developed a scoring rubric. The interpretation task was worth 24 points (Fig. S1 [footnote 1]). Questions 1, 2, 3, 6, 6b, 8, and 10 were scored on both the sequence stratigraphic and Wheeler diagrams. Questions 4, 5, 6a, and 7 required students

[1]Supplemental Material. Figure S1: This figure is the geologic packet that students completed in this study including the geologic task with a sequence stratigraphic and Wheeler diagram. Figure S2: Students completed a knowledge survey that assessed students' basic understanding and spatial understanding of important sequence stratigraphic concepts. Figure S3: A represents the Homoscedasticity plot for student scores on the disembedding test and B represents the homoscedasticity for student scores for mental folding and unfolding. Please visit https://doi.org/10.1130/GEOS.S.19067168 to access the supplemental material, and contact editing@geosociety.org with any questions.

to provide a single answer about the diagrams rather than an answer for each diagram and were only scored once. Scoring included a combination of full and partial credit. For example, for question 8, students identified packages representing low sea levels or the lowstand systems tracts (Fig. 2A). Students who identified the correct layers, but included some additional layers, were given partial credit (Fig. 2B). Additionally, partial credit was awarded to students who only marked one type of facies (marine shale or nearshore sands) in the correct package (Fig. 2C). No penalties were given for incorrect answers or unanswered questions.

Cronbach's alpha was used to evaluate how well items on the sequence stratigraphic task were correlated to one another. The alpha of 0.713 was within the range of acceptable values (0.7–0.95) (Tavakol and Dennick, 2011), indicating that the items all measure the same variable (i.e., sequence stratigraphic interpretation). One question (question 9), which required participants to outline a prograding shoreline, was removed from scoring because an item-level analysis and Cronbach's alpha indicated poor alignment with the rest of the task.

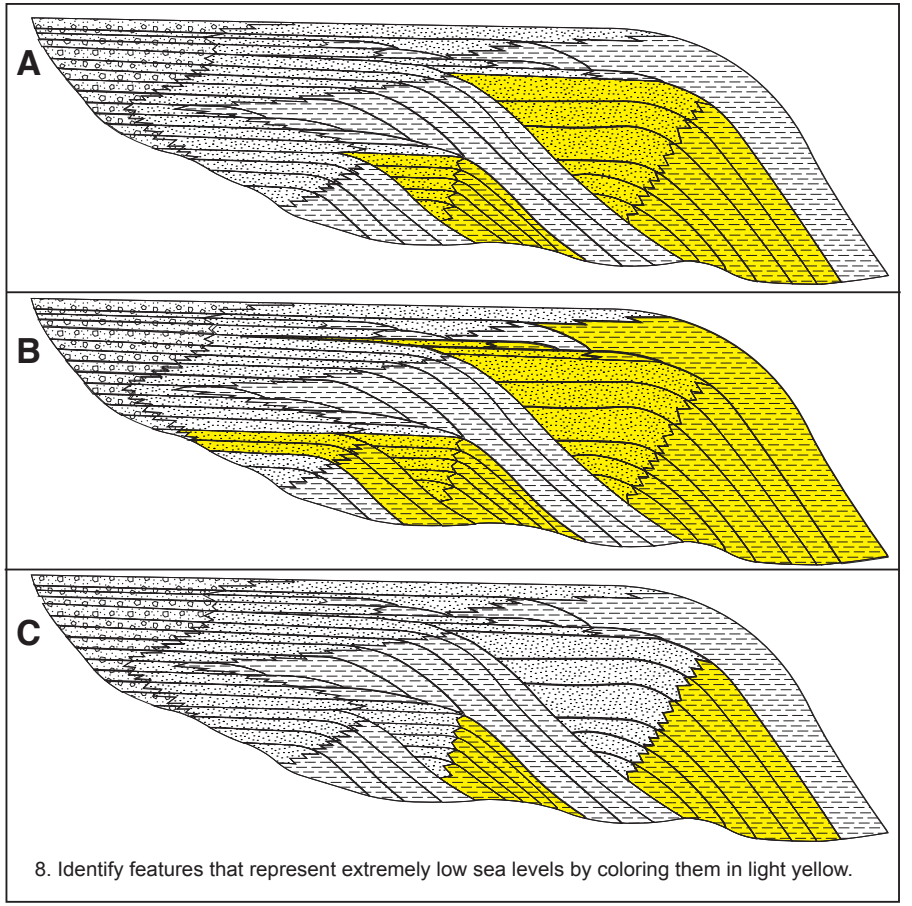

Figure 2. Example of possible student answers for scoring question 8 from the task demonstrating full (A) and partial credit (B and C) on a sequence stratigraphic diagram. B shows an example of an answer with additional layers included; C shows an example of an answer from a student who chose the correct packages but only colored in one of the facies.

Knowledge and Experience Survey

The knowledge survey consisted of 10 items to assess students' understanding of the spatial aspects of sequence stratigraphic concepts (e.g., base level, sedimentation rate, eustasy, and relative sea level) (Fig. S2 [footnote 1]). Three questions targeted known student errors from the geoscience education research literature, such as associating thickness with sedimentation rate (Cheek, 2013; Herrera and Riggs, 2013a). Seven other questions assessed knowledge of prevalent concepts in the task but did not overlap with the task itself (e.g., recognizing sea-level rise or fall based on a succession of sedimentary rocks). The 10 items consisted of three multiple-choice questions and seven questions that required a short answer or identification of a feature on a diagram (e.g., they were asked where base level is along the river's profile from mountain to ocean). The knowledge survey was scored using expert-generated correct answers. Students only received points for correct answers and no penalties were given for incorrect answers or no answers at all. An expert review was conducted for question style and content. Two experts participated in generating the correct scores and the expert review: Expert one has 10 years of experience teaching sequence stratigraphy and related content and the second expert has more than 20 years of similar experience.

Hidden Figures Test

The hidden figures test is designed to evaluate the cognitive process referred to as flexibility of

closure (Ekstrom et al., 1976b), which we used to measure disembedding. Flexibility of closure refers to one's "ability to hold a given visual percept or configuration in mind so as to disembed it from other well-defined perceptual material" (Ekstrom et al., 1976b, p. 20). In other words, the test measured how well one can distinguish an individual shape or pattern within a noisy background. The test provided students with a target form. Their task was to decide if the target was present in a set of figures by placing an "X" below that figure. If the model was not present, an "O" was placed instead (Fig. 3A). This test had two parts consisting of 200 patterns each (Ekstrom et al., 1976b). Only part A of the test was administered to conserve instructional time. Students had three minutes to complete part A (Ekstrom et al., 1976b). The test was scored based on Ekstrom et al. (1976b). Students received one point per correct answer and lost a quarter of a point for every wrong answer. In other words, an "X" placed where an "O" should have been was worth –0.25 points. Students did not receive penalties for unanswered questions. Some students only placed "X" where they saw the model and did not place "O" where they did not see the model. In this case, all unanswered patterns before the final "X" were assumed "O" and scored accordingly. A maximum of 200 points was possible for this test.

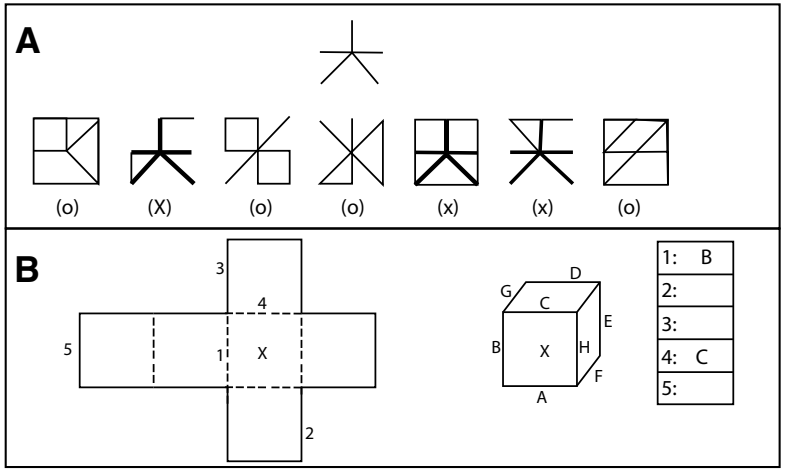

Figure 3. (A) Example of what a question on the hidden figures test may look like. The model is bolded within the response options. (B) Example of what a question on the surface development test may look like.

Surface Development Test

The surface development test was designed to evaluate an individual's skill in mentally manipulating one spatial arrangement into another (Ekstrom et al., 1976b). This test assessed the students' mental skill in folding or unfolding a given object. The test provided participants with an image of a piece of paper, with numbered edges, that can fold into the corresponding object with lettered edges. The task was to determine which numbered edges from the paper, when folded, would correspond with lettered edges on the object (Ekstrom et al., 1976a) (Fig. 3B). The test consisted of six sets of images with five edges to match in each (Ekstrom et al., 1976a). Participants had six minutes to complete the task (Ekstrom et al., 1976a) and were scored based on Ekstrom et al. (1976b) using the same scoring style as for the hidden figures test. A maximum of 30 points was possible on the surface development test.

Data Collection

Faculty and Student Recruitment

A snowball method, in which initial faculty were contacted to participate in this study and then provided names of additional faculty who teach similar courses to be contacted, was used to recruit faculty who taught sequence stratigraphic concepts including Wheeler diagrams. Initial introductions were made via email, and faculty who agreed to participate provided 1.5 classroom sessions for the study to be conducted. Students enrolled in the participating courses were asked to consent to participate in the study based on Institutional Review Board approval (Human Subjects number HS19-0049). All students completed the task and corresponding skills tests. The tasks provided all students with additional practice of course content. Only data for students who consented to be in the study were retained.

Timeline

Development, pilot testing, and revision of the study materials were completed between January 2018 and January 2019. Data were collected at all three universities during the spring 2019 semester. An additional set of data was collected from university 3 during the fall 2019 semester.

Implementation

Before data collection, the course faculty had completed lectures on sequence stratigraphic concepts, including introducing sequence stratigraphic diagrams and Wheeler diagrams. All faculty delivered their instruction as they would typically do during this course to ensure the study outcomes represent typical student knowledge gained from regular course instruction. The faculty consented to have the lecture recorded and provided copies

of all lecture materials so the researchers could ensure the same content was covered in all courses. As part of the standard instruction, students completed a Wheeler diagram activity that included creating a Wheeler diagram and identifying major surfaces and packages. University 1 and university 3 faculty both used the Jerry Baum activity, whereas university 2 faculty used an activity they developed but that covered the same material.

Students were introduced to the lead author as the researcher and provided consent to participate in the study. Each student was instructed to answer each question on both the sequence stratigraphic diagram and the Wheeler diagram (Fig. 4). Subsequently, participants were given unlimited time to complete the knowledge and experience survey. Finally, the researcher read the first timed spatial test instructions for the hidden figures test. All students started the test together and were instructed to stop working when the three minutes had passed. The researcher completed the same steps for the six-minute surface development test. At the end of this test, students turned in their packets and sets of colored pencils.

Data Analysis

One student did not consent and was removed from the data set. All data were scored and digitized. Descriptive statistics and tests of assumptions for regression analysis were analyzed using IBM SPSS Statistics 25 software. Next, the data were formatted and entered into the R 3.6.2 statistical computing environment using the RStudio interface for linear regression and nested linear regression to assess the predictive ability of spatial skill for sequence stratigraphic interpretation.

RESULTS

Descriptive Statistics

Descriptive statistics are reported in Table 3 and demonstrate that the assumptions of normality (skewness and kurtosis) are met for all data sources

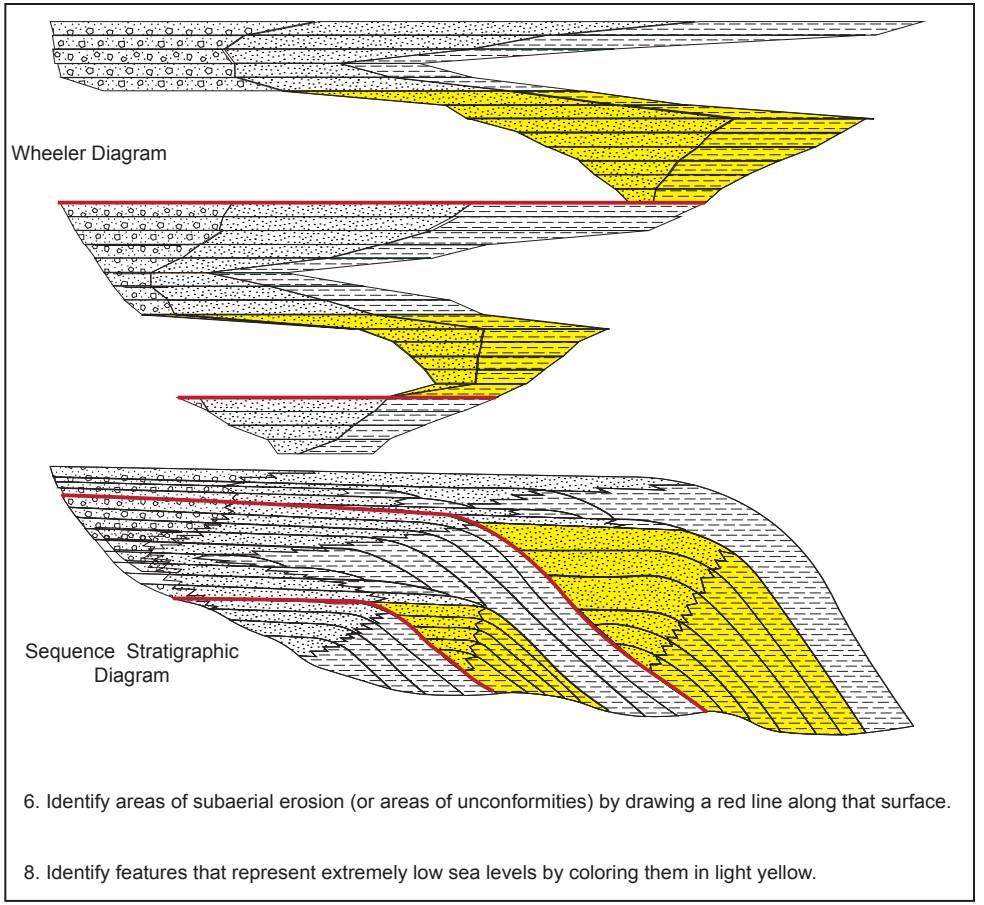

Figure 4. Example of the correct answers for questions 6 and 8 had the student answered them on both the Wheeler and sequence stratigraphic diagrams. Note how students may use the two spatial skills: Students must disembed the figure to find the unconformity (sequence boundary) on the sequence diagram; they then need to work between the two diagrams, mentally unfolding the sequence diagram into the Wheeler diagram's horizontal time layers.

TABLE 3. DESCRIPTIVE STATISTICS

Instrument	*N*	Total possible points	Mean	SD	Range	Skewness	Kurtosis
Surface development test	78	30	17.6	8.50	1.25–30.00	–0.15	–1.21
Hidden figures test	78	200	98.8	23.48	39.25–147.75	–0.44	0.03
Sequence stratigraphic task	78	24	7.34	4.13	0.00–16.00	0.31	–0.69

Note: The Knowledge and Experience survey was not included here as it does not provide insight into the statistical relationship between students' spatial skill and sequence stratigraphy interpretation skill. *N*—total number of participants, SD—standard deviation.

(surface development test, hidden figures test, and the sequence stratigraphic task). The skewness and kurtosis of each measure were <1, reflective of a normal distribution. Negative kurtosis for the surface development test indicates a flatter curve than a typical normal distribution, with fewer outliers than expected. The data set met the assumptions of linearity. The linearity test assesses whether a linear relationship exists between each spatial skill and the geologic task. A *p*-value for the deviation from linearity >0.05 is thought to represent a linear relationship and meet the assumption. The linear relation between the sequence stratigraphic task and disembedding was $p = 0.073$, and the linear relationship between the sequence stratigraphic task and mental folding and unfolding was $p = 0.789$. Because both relationships have a *p*-value >0.05, they are thought to have a linear relationship. Additionally, assumptions of homoscedasticity were also met. Homoscedasticity refers to the assumption that the residuals of the data are randomly dispersed and is assessed via a scatter plot of the residuals (Fig. S3 [footnote 1]). One outlier was removed for having a combined task score greater than two standard deviations above the mean. It is notable that when looking the hidden figures test and surface development test, students' scores range from very low to very high, which shows the dynamic range of upper-division geology majors' spatial skills (Table 3).

All correlations between tests (hidden figures test, surface development test, and the sequence stratigraphic interpretation task) were significant (Table 4). This means that there is a linear relationship between the independent variables. Significant correlations between the spatial tests and the dependent variable (the sequence stratigraphic interpretation task) suggest it is worthwhile to include these variables in a regression analysis.

TABLE 4. CORRELATION TABLE

Variables	1	2	3
1. Sequence stratigraphic + Wheeler diagram task	1.00	—	—
2. Hidden figures test	0.26*	1.00	—
3. Surface development test	0.49*	0.42*	1.00

Note: Table provides the correlation matrix which describes the linear relationship between each variable. The diagonal correlates each variable with itself and therefore is a perfect linear relationship ($r = 1.00$). Em dash indicates a repeat of data already in table.
*Indicates correlation is significant at $p < 0.05$.
**Indicates correlation is significant $p < 0.01$.

TABLE 5. REGRESSION FOR SPATIAL TESTS AND INTERPRETATION TASK SCORE

Variable	Multiple R^2	Adjusted R^2	*F*-statistic	*df*	*p*
Disembedding	0.05	0.04	4.25	76	0.041*
Mental folding and unfolding	0.26	0.25	26.67	76	0.000†

*$p < 0.05$.
†$p < 0.000$.
Note: Multiple R^2 is a goodness-of-fit statistic representing the amount of variance in students' interpretation task scores (dependent variable) explained by the spatial skills (independent variables). Adjusted R^2 accounts for the unique variance of only one independent variable rather than all independent variables in the model (e.g., disembedding and mental folding/unfolding). *F*-statistic assesses if two means are statistically different. In the case of regression, the *F*-statistic compares the regression coefficients to the null hypothesis that the coefficients are zero. *df*—degrees of freedom. *p*—significance of the *F*-statistic.

TABLE 6. NESTED REGRESSION FOR SPATIAL TESTS AND INTERPRETATION TASK SCORE

Variable	Multiple R^2	Adjusted R^2	*F*-statistic	*df*	*p*
Mental folding and unfolding	0.25	0.25	29.97	76	0.000*
Mental folding and unfolding + disembedding	0.26	0.24	13.17	75	0.000*

*$p < 0.000$.
Note: Multiple R^2 is the amount of variance each spatial skill makes up for in students' Interpretation task scores. Adjusted R^2 values adjust the Multiple R^2 value to account for the number of predictors in the regression (1 for each test). The *F*-statistic assesses in the means of two samples are statistically different. *df*—degrees of freedom. The *p*-value tells if the regression test was significant. A nested regression inputs the independent variables (e.g., disembedding, mental folding/unfolding) in a series to evaluate the unique contributions of adding additional independent variables. In this case, adding disembedding accounts for 0.01 additional variance in the dependent variable.

Linear Regression

A set of linear regressions was run to assess the predictive ability of each skill for the sequence stratigraphic task score. First, disembedding scores were regressed on the combined task score (Table 5); the result of this regression was significant and accounted for 6.6% of the variance in the scores. Second, the mental folding and unfolding score was regressed on the combined task score, resulting in a significant regression accounting for 24.4% of the variance in the combined task score (Table 5).

Nested Regression

Mental folding and unfolding correlates with disembedding ($r = 0.4$), so it is likely that the two spatial skills account for some amount of overlapping variance in the sequence stratigraphic task. To explore this possibility, a set of nested regressions were run with mental folding and unfolding

as the primary variable because it accounts for the most individual variance. The nested models show that mental folding and unfolding accounts for the overwhelming majority of the variance, with disembedding adding in an additional 0.1% (Table 6). The disembedding test accounted for almost no unique variance. In other words, whatever skill was responsible for the correlation between disembedding performance and sequence stratigraphic task performance was also required for the mental folding and unfolding test.

DISCUSSION

Revisiting our research questions, we first considered whether spatial visualization predicted student scores on a sequence stratigraphy task. We found that, yes, spatial skill was related to student sequence stratigraphic interpretation. Second, we asked which spatial visualization skills are important for student performance on a sequence stratigraphic task. Our results indicate mental folding and unfolding is related to students' sequence stratigraphic interpretation skills. While disembedding alone appeared to be important to the task, when nested with mental folding and unfolding, the variance added by disembedding was negligible.

Disembedding

The results indicate that disembedding may not be a significant predictor of sequence stratigraphic interpretation. On its face, this finding appears to contradict the Kastens and Ishikawa (2006) hypothesis that seismic reflection profile analysis would benefit from disembedding skill. Additionally, the results do not confirm the Kreager (2021) hypothesis that sequence stratigraphic diagrams may be a stepping stone for novices to learn how to complete interpretations of seismic profiles, which require novices to disembed the image. However, the surface development test and the hidden figures test were correlated with each other. We hypothesize that to complete the surface development test, some level of disembedding is required. Thus, the variance due to disembedding skill necessary for sequence stratigraphic interpretation is accounted for by the disembedding skill necessary to complete the surface development test. Though few tests of disembedding exist, there may be value in running a similar study administering a different test of disembedding that may be more distinct from the surface development test.

Beyond the results of the regression tests, our study found a wide range of student disembedding skill, with student scores ranging from 39.25 to 147.75 out of 200 possible points on the hidden figures test. Our findings mirror those of Ormand et al. (2014) and Gold et al. (2018), who found that geology majors' skills vary greatly on spatial tests.

Mental Folding and Unfolding

This study is the first to test the value of mental folding and unfolding for geoscience tasks. Mental folding and unfolding is a skill that Kastens and Ishikawa (2006) suggested may relate to geologic tasks, such as interpreting structurally folded beds. Kreager (2021) proposed that mental folding and unfolding is necessary for sequence stratigraphy because important features invisible between layers in the sequence stratigraphic diagram are visible in the Wheeler diagram. Further, the creation of Wheeler diagrams is a routine part of the workflow for seismic sequence stratigraphy despite being cumbersome and time consuming (Qayyum et al., 2012).

Our data show that mental folding and unfolding is positively correlated with student performance on a sequence stratigraphic interpretation task. Although our findings are correlational and the direction of causation is unclear, this result is consistent with the hypothesis that low mental folding and unfolding skill may be a barrier to success in sequence stratigraphy interpretation. Heath's (2000) survey of 400 petroleum companies suggests that sequence stratigraphic interpretation skill is one of the top six skills companies seek in new employees. If students with low mental folding and unfolding skills cannot complete novice-level tasks that mimic the expert-level tasks, they may not be able to progress successfully beyond initial stages of learning or at a rate expected by employers.

Although performance on the sequence stratigraphic and Wheeler diagrams was highly correlated ($r = 0.89$), the correlation was not perfect, therefore it is possible that some individuals may be more likely to succeed with one type of diagram than the other. Wheeler diagrams are an integral part of seismic sequence stratigraphy at the expert level. Thus, the inability to interpret the correspondence between a Wheeler diagram and a sequence stratigraphic diagram may result in a failure to initially succeed. Individuals who are struggling could benefit from training to develop their interpretation skills or structuring workflows (e.g., which diagram they choose to make initial interpretations, or how they choose to tackle these types of interpretations), perhaps assisted by artificial intelligence (Shipley and Tikoff, 2019) to reduce the need for such skills.

Implication for Teaching Sequence Stratigraphy

Results of this study provide a foundation for instructors, trainers, and researchers to think about the needs of novices (e.g., students, early-career employees or researchers, etc.). Here we provide some suggestions for training within these settings. Instructors should consider training mental folding through authentic geologic tasks. It is important to note that no literature currently assesses the malleability of either the mental folding and unfolding or disembedding skill, and continued research on how to train these skills in the classroom is needed. Despite this, based on other literature on training spatial skills (e.g., Uttal et al., 2013; Ormand et al., 2017), we suggest modeling and teaching students to gesture, providing multiple examples, and encouraging practice working between the diagrams as ways to help improve student interpretation skills.

Herrera and Riggs (2013b) assessed students' gestures while they discussed sedimentary processes related to sequence stratigraphy and found that students used a range of gestures and commonly related them to verbal metaphors. Gestures

can help reduce the cognitive demand of complex tasks (Goldin-Meadow et al., 2001). *The Spatial Thinking Workbook* (Ormand et al., 2017) explains that gesturing helps students externalize their mental models of geologic structures and processes to support their reasoning and allows instructors to "see" what their students are thinking. While gesturing and sketching both allow students to externalize a mental model, gestures are transient, and so students are not stuck if the model is substantively incorrect. We recommend instructors engage in gesturing and encourage students to gesture as they work through sequence stratigraphic interpretation problems.

Alcalde et al. (2017) investigated students' interpretations of subsurface faults and found that their errors were caused by incorrectly applying example faults from their training to the new context. The authors suggested increasing students' exposure to different types of sequences to increase their abilities to identify features. For sequence stratigraphy, we recommend engaging students in comparing common patterns representative of specific features. For example, onlapping surfaces commonly represent the location of an unconformity, yet the appearance of an onlapping surface varies between examples. Engaging students in identifying the same feature across multiple examples will promote their abilities to identify the key patterns for a given feature.

In a study of the impact of Wheeler diagram instruction on sequence stratigraphic task performance, Kreager (2021) found that Wheeler diagrams facilitated understanding of sequences for some students. We suggest increased practice working between Wheeler and sequence stratigraphic diagrams, such as in the sequence stratigraphic task or the original task by Jerry Baum, to provide students with practice of the spatial skill of mental folding and unfolding. Having students create the Wheeler diagram in the Blume activity also adds in a product of sketching, another strategy that increases spatial skills (Ormand et al., 2017). For large classes, an alternative, expedient way to gauge students' ability to interpret and relate complex diagrams is to engage them in formative assessment using click-on-diagram questions on phones, tablets, or computers (LaDue and Shipley, 2018). Posing questions where students need to identify sequence stratigraphic features and make predictions based on processes by clicking on diagrams provides the instructor with real-time feedback on student understanding of basic concepts and how the diagrams relate to each other.

Limitations and Future Work

The present study was conducted with a sample set of students receiving instruction from three different professors. This intentional component of the study design mirrors standard instructional practice rather than conducting an intervention study, where one consistent set of teaching materials might be used to introduce sequence stratigraphy and Wheeler diagrams. Therefore, this study is tied to the students' learning experience (Loyd et al., 2005) but does not definitely demonstrate a causal role of spatial skills in interpretation. Because the relationship between spatial skill and sequence stratigraphic interpretation is correlational, the direction of causal influence is unclear. It is possible that an unidentified third variable might be influencing performance on both the spatial tests and the interpretation tasks. We attempted to rule out general intelligence, which is known to correlate with spatial skill, as one potential third variable (Carroll, 1993; Ebisch et al., 2012). In an effort to distinguish the contribution of spatial skill from general intelligence, we administered a measure of fluid intelligence (e.g., letter series completion test). However, the test was determined to be too difficult because all of the students scored a one or zero on the 15-item test. Future work could address this issue by including a more accessible fluid intelligence test or employing an intervention design to determine the underlying causal structures.

Finally, while it would be of interest to know whether any of the methods of training or level of prior training were important, the numbers of participants did not provide sufficient power to pursue such questions. We note for the two universities that contributed the largest numbers of participants, universities 2 and 3, there were no significant differences in means (based on a t-test [$t(74) = 0.287$, $p = 0.775$]) or standard deviation (based on an F-test [$F(64) = 0.856$, $p = 0.328$]) for students' score on the combined sequence stratigraphic task.

The present findings revealed a new set of questions about the nature of the relation between spatial skills and sequence stratigraphic interpretation. Future work should assess how disembedding and mental unfolding impact sequence stratigraphic interpretation through qualitative assessment. Qualitative observations would allow researchers to collect data on how students use the spatial skills to solve tasks for sequence stratigraphic interpretation. The addition of this analysis may also reveal more about the overlap between the two spatial skills and further explain the results of the nested regressions. Analysis of students' errors is also crucial for understanding how to train these skills. If mental folding and unfolding is as important as our results suggest, undergraduate- and graduate-level courses could investigate the value of training students' spatial skills in the classroom. Identifying what errors students make and how those errors relate to specific spatial skills should provide insight into targeted training strategies.

We initially hypothesized that disembedding would be necessary for this sequence stratigraphic task because it seemed to be important for interpreting a sequence stratigraphic diagram. Mental folding and unfolding, which we proposed is needed to move between the sequence stratigraphic and Wheeler diagrams, accounted for all of the disembedding variance. Therefore, the role of disembedding in sequence interpretation is an open question. Future work should examine whether student interpretation skill for only a sequence stratigraphic diagram task is different than for a task with both Wheeler and sequence stratigraphic diagrams. To determine the value of Wheeler diagrams in instruction, studies should examine Wheeler diagrams as a learning tool by assessing student interpretation scores pre– and post–Wheeler diagram instruction or compare student outcomes for courses teaching Wheeler diagrams before and after sequence stratigraphic diagram interpretation. The faculty teaching courses for the present study taught sequence stratigraphic concepts and

sequence stratigraphic diagrams before teaching Wheeler diagrams. During the recruitment phase, one experienced geoscience educator communicated that they teach Wheeler diagrams before introducing sequence stratigraphic diagrams because they believed understanding chronostratigraphic diagrams makes understanding the spatiotemporal nature of the concepts easier to grasp (D. Budd, 2019, personal commun.).

CONCLUSIONS

The petroleum industry (Krantz et al., 2016a; Summa et al., 2017) and the GER community (e.g., Kastens and Ishikawa, 2006; Ormand et al., 2014; Atit et al., 2015; Newcombe and Shipley, 2015; McNeal et al., 2019; Hannula, 2019) emphasize the importance of spatial thinking, yet little is known about the relationship between spatial skill and sequence stratigraphy. This study addressed two of the three grand challenges for research in the spatial and temporal thinking set forth for the Community Framework for Geoscience Education Research (St. John, 2018). Addressing the first grand challenge, "What skills and tasks are essential to the different specialties within the geosciences?" (Ryker et al., 2018, p. 70), this study is the first to test the link between spatial skill and sequence stratigraphic diagram interpretation. The results confirmed that mental folding and unfolding is associated with sequence stratigraphic interpretation and are inconclusive about whether disembedding skill is uniquely important for interpretation.

The second grand challenge related to spatial and temporal thinking is: "Do current measures of spatial and temporal reasoning accurately assess the skills required in the various geoscience specialties? If not, what other types of assessments need to be developed?" (Ryker et al., 2018, p. 70). The present study addresses this grand challenge because it is the first to assess the value of mental folding and unfolding skill in the geosciences. The findings demonstrated that the surface development test correlated with geologic tasks that required mental folding and unfolding skills and support using this test for assessment of skills in the geosciences. The overlap in variance shown between the two spatial skills (mental folding and unfolding and disembedding) in the nested model may mean that some portion of disembedding skill is being accounted for in the surface development test. Future studies with alternative measures of disembedding may clarify its importance for geoscience problem solving. The findings also suggested that low mental folding and unfolding skill might be a barrier to success in sequence stratigraphy interpretation, and support for such skill might be an important consideration in curriculum development.

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