Research on Cognitive Domain in Geoscience Learning: Temporal and Spatial Reasoning

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Introduction

The geosciences are characterized by their particular application of and reliance on temporal and spatial reasoning. Geoscientists must be able to apply their knowledge across a variety of scales. In the words of Arthur Conan Doyle in his book A Study in Scarlet, "*From a drop of water, a logician could infer the possibility of an Atlantic or a Niagara without having seen or heard of one or the other. So all life is a great chain, the nature of which is known whenever we are shown a single link of it.*" Geoscientists should be able to look at, say, physical and chemical differences in ocean surface waters (Figure 1) or in sedimentary layers from a core of the seafloor and infer changes in patterns (spatial) over time (temporal). The ability to engage with this kind of task represents a great shift in thinking from where most students begin their studies, be that in K-12 or college. In order to understand how people's ability to spatial and temporal reasoning changes over time requires us to identify what skills are essential, how to properly assess those skills, and then to explore the impacts of different targeted interventions in geoscience contexts.

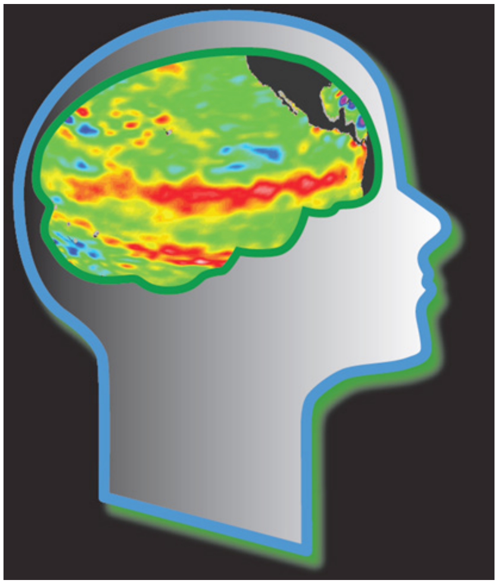

Figure 1. Developing a geoscience understanding of Earth processes requires thinking across different spatial and temporal scales, such as those involved with changing El Niño-La Niña conditions inferred from NASA sea surface height anomaly data in the equatorial Pacific Ocean as shown here. Figure originally created by Kirk and Pisolesi for the cover of Kastens and Manduca (2012), Earth and Mind II: A Synthesis of Research on Thinking and Learning in the geosciences. GSA, v. 486.

While more is known about how people reason spatially as compared with temporally, there are still significant gaps in our understanding of spatial reasoning in the geosciences. We believe that there are opportunities to build on lessons learned from previous investigations of spatial thinking (e.g. the Spatial Intelligence and Learning Center, or SILC), including how a community can investigate a specific line of reasoning. There is also a need to build on established research from other domains, from anthropology to cognitive science to physics.

We identified three Grand Challenges to better understand the need for and growth of spatial and temporal reasoning in geoscience education. These include identifying what reasonings or skills are essential to the geosciences (both broadly and within subdisciplines), and the intertwined challenge of how to assess those reasonings and use those results to improve on what students are learning from their geoscience experiences.

Grand Challenges

Grand Challenge 1: What skills and tasks are essential to the different specialties within the geosciences? What spatial and temporal reasoning skills map onto these specific tasks?

To ensure that our work is relevant to the broader geoscience community, we need to target our research to the primary specialties within the community (e.g., perhaps as defined by AGU's sections or GSA's divisions). Because these specialties can vary greatly in terms of their scale, scope, and methods, it is necessary to identify the primary defining skills and tasks in each area. Once the essential tasks and skills of these specialties are identified, the types of spatial and temporal reasoning in each need to be "mapped" so we can understand if and how these fields differ.

Grand Challenge 2: 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?

With an understanding of the essential tasks required in each of the primary specialties in the geosciences, we can then proceed to empirically test whether these tasks actually recruit the spatial and temporal reasoning skills that were "mapped" in GC 1. That is, if we think locating fossils requires penetrative thinking, disembedding, mental rotation, and transformation, does performance on these measures predict success in fossil locations and identification? Are there any domain-specific geoscience tasks or skills that do not seem to align with an existing spatial or temporal reasoning measure? If not, can we design a more appropriate measure?

Grand Challenge 3: How can geoscience education foster the spatial and temporal reasoning skills that are required in each specialty?

With an understanding of the essential types of spatial and temporal reasoning for each geoscience specialty, and an understanding of how to measure them, we can then proceed to develop and assess instructional methods that support these specific skills. Specific instructional manipulations can be conducted with the intention of assessing how these interventions support content learning, but also how they support the development of spatial and temporal reasoning. If two different specialties require the same variety of spatial or temporal reasoning, can the same style of instructional intervention be used in both context?

Grand Challenge 1:

What skills and tasks are essential to the different specialties within the geosciences? What spatial and temporal reasoning skills map onto these specific tasks?

Rationale

To ensure that our work is relevant to the broader geoscience community, we first need to focus the research on the primary specialties within the community, for example using AGU's sections or GSA's divisions. Because these specialties can vary greatly in terms of their scale, scope, and methods, it is necessary to identify the primary defining skills and tasks in each area.

Several efforts have been made to summarize the kinds of skills and tasks necessary to master in order to be a geoscientist. For example, the 2014 Summit on the Future of Undergraduate Geoscience Education brought together ~200 post-secondary educators and representatives from industry and professional geoscience societies. The Report from that meeting stresses that geoscientists "need to be able to think spatially and temporally... [and] think critically and readily solve problems, especially those requiring spatial and temporal (i.e. 3D and 4D) interpretations" (Mosher et al., 2014). In a survey following the Summit, "problem-solving with spatial and temporal data" was ranked as the second most critical geoscience (non-professional scientist) skill in undergraduate education (Survey Results), with more than 60% of 455 respondents identifying it as "very important." Further, attendees of the Geoscience Employers Workshop provided thoughts on the various concepts they thought geoscience graduates should be able to understand (Meeting Outcome). Many of these concepts rely on spatial and temporal thinking, including understanding how systems work and interact, geological time/Earth evolution, age dating, events and rates, and landscape alteration (i.e., geomorphology).

Researchers have also tried to make sense of the complex array of spatial and temporal skills required for geoscientists (Kastens & Ishikawa, 2006; Liben & Titus, 2012; Newcombe & Shipley, 2015; Tarampi et al., 2016; Zen, 2001; Krantz, Ormand, & Freeman, 2013; Cervato & Frodeman, 2012). Some of these tasks include things like "recognizing, describing, and classifying the shape of an object; describing the position and orientation of objects; making and using maps; envisioning processes in three dimensions; and using spatial-thinking strategies to think about nonspatial phenomena" (Kastens & Ishikawa, 2006). A 2009 report by Kastens and others suggested that geoscientists possess a distinctive set of approaches and perspectives when it comes to studying the Earth. Specifically, they identified four themes in how geoscientists think and learn which includes their ability to think about time, their understanding of the earth as a complex and complicated system, their experience with categorization, identification and transformation in fieldwork, and their use of spatial thinking for interpreting visualizations and seeing patterns in data. These four themes are meant to generalize across all specialties within the geosciences, but it is likely the case that some skills and tasks are more (or less) critical to certain specialties. For example, map reading (spatial) and time-sequenced data interpretation are important to many specialties such as ocean sciences and global environmental change, but may be less immediately important to other specialties (e.g. a geochemist doing bulk chemical analysis to assess re-opening an old quarry might not be as concerned with temporal data, but could still want to map where their samples came from and the extent of the potential quarry). Once the essential tasks and skills of these specialties are identified, the types of spatial and temporal reasoning in each needs to be "mapped" so the community can understand if and how these fields differ.

Recommended Research Strategies

1. Kastens & Manduca (2012) created concept maps of Spatial Thinking and Temporal Thinking in Geosciences (Figure 2). These should be revisited and used as a model for creating a map of the various kinds of spatial and temporal reasoning skills and the geoscience specialties that rely on these skills. This kind of representation would allow us to see where specialists may overlap in particular skills and where they may draw upon a unique set of skills.

2. While some specialties within Geoscience have been investigated in terms of the kinds of spatial and temporal reasoning they require (e.g., Tarampi et al., 2016), many have not. Thus, an important research strategy is to conduct process and task analyses in these less explored specialities to make inferences about how the geoscience skill aligns with spatial or temporal reasoning skills. For example, it could be said that the field of paleontology requires spatial thinking in the form of penetrative thinking, disembedding, mental rotation, and mental transformation. That is, locating fossils requires being able to imagine the layers of rock (penetrative thinking), being able to "see" relevant structures within the rock (disembedding), and the ability to mentally rotate fossils (mental rotation) in order to generate inferences about what the entire creature should look like (mental transformation).

3. Select specific, well-defined areas of geoscience and have people in those fields describe the spatial and temporal tasks they do as part of their job in focus groups. We recommend that focus groups might help elicit more ideas than one-on-one interviews or surveys. This cognitive task analysis with specific experts could be used to identify the most important, or essential, spatial and temporal reasoning tasks they do. This could also be completed as a modified Delphi study, or by studying geoscientists doing expert tasks, and coding for different reasonings being used.

Grand Challenge 2:

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?

Rationale

Before assessing a spatial or temporal reasoning skill, a researcher must first establish that the particular reasoning they are studying is critical to some aspect of success in the geosciences (see GC 1). With an understanding of the essential types of spatial and temporal reasoning required by the primary geoscience specialties and tasks, we can then proceed to empirically test whether these tasks actually recruit the spatial and temporal reasoning skills that were "mapped" in GC 1. That is, if we think locating fossils requires penetrative thinking, disembedding, mental rotation, and transformation, does performance on these measures predict success in predicting fossil locations? If through this investigation there are domain-specific geoscience tasks or skills found that do not seem to align with an existing spatial or temporal reasoning measure, an important next step would be to design a more appropriate measure.

Measurement is a critical part of documenting student progress towards skill mastery, and assessing the impacts of different learning experiences (see GC 3). Many tools already exist, especially to assess spatial thinking (see spatiallearning.org for some examples), while others likely need to be developed. For example, Resnick & Shipley (2013) introduced a new measure to assess mental brittle transformation in order to distinguish some of the differences in visualization practices between geologists and organic chemists, while Dodick & Orion (2006) designed three instruments to measure perceptions of time with middle and high school students. Previous studies have used a wide array of measurement instruments to measure spatial thinking including the Geologic Block Cross-Sectioning Test (used by Atit, Gagnier, & Shipley, 2015), the Topographic Map Assessment, visualization, rotation and perceptual speed tests (used in Hambrick et al., 2012) and open-ended interviews with children (Ault, 1982) to assess different types of spatial thinking (e.g. mental rotation, penetrative thinking and disembedding in Ormand et al., 2014). Temporal thinking has received less attention, but instruments include the Geological Time Aptitude Test (GeoTAT, used in Dodick & Orion, 2003a), the Temporal Spatial Test and Strategic Factors Test (TST and SFT, respectively; used in Dodick & Orion, 2003b).

Newcombe & Shipley (2015) provide a recent review of the types of spatial thinking and assessments on spatial thinking, especially on measures for disembedding, spatial visualization, mental rotation, spatial perception and perspective taking. Uttal & Cohen (2012) and Uttal et al., (2013) reviewed studies that assessed the impact of spatial training; these reviews included reference to numerous spatial assessment instruments. Determining which of the current instruments measure domain-specific geoscience tasks or skills is an important next step.

With respect to temporal thinking, Shipp, Edwards, & Lambert, (2009) provides an extensive review of temporal focus ("the attention individuals devote to thinking about the past, present, and future," p. 1), as well as a brief overview of the other temporal constructs including a short definition, sample measures, whether the domain assessed is cognitive, affective or behavioral, and known covariates or consequences. These dimensions include time perspective, temporal orientation, temporal depth, time attitude, preferred polychronicity, hurriedness and pacing style, and have not been addressed in depth within the geoscience education research literature.

Recommended Research Strategies

1. Additional literature reviews would be of great benefit in establishing what assessment tools already exist and what they measure. These would be invaluable in bringing together disparate literature from cognitive science and other DBER fields, like Physics Education Research (PER; e.g., Dori & Bara, 2001 examined the development of spatial understanding using virtual and physical molecular modeling).

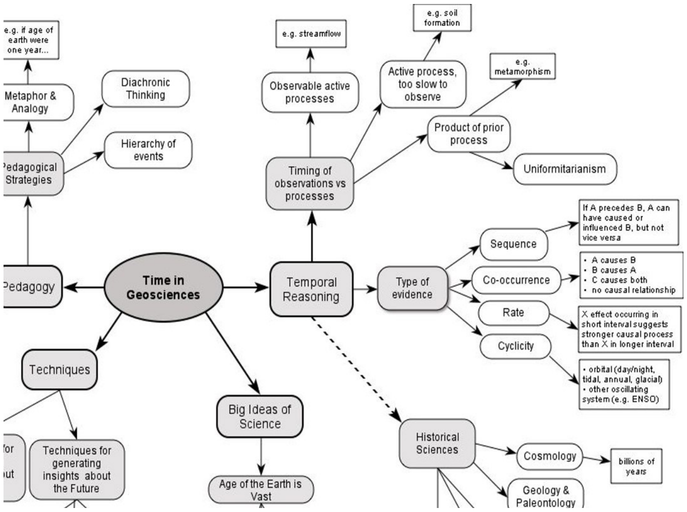

Figure 2. Kastens and Manduca's (2012) concept maps of spatial and temporal thinking in the geosciences may serve as a starting point for an important next step in research: creating a map of the various kinds of spatial and temporal reasoning skills and the geoscience specialties that rely on these skills. For example, being able to apply the principle of superposition to a rock outcrop is a specific skill that could be mapped onto the sequence type of temporal thinking.

2. Proof of concept tests are needed to assess the "fit" of existing assessment tools. For example, if we hypothesize X domain-specific task requires Y type of spatial reasoning (see Grand Challenge 1), do we see that spatial reasoning test predicting performance of the domain specific task? Going further with that example, we might assume that mapping a bedrock anticline requires penetrative thinking; is someone's ability to map that anticline correlated with measures of penetrative thinking?

3. Identify or develop additional metrics as appropriate to assess the spatial and temporal nature of geoscience tasks. This is a follow-up to Strategy 2 that may be necessary if domain-specific tasks are not found to correlate with existing measures of spatial and temporal thinking.

Grand Challenge 3:

How can geoscience education foster the spatial and temporal reasoning skills that are required in each sub-specialty?

Rationale

Once an understanding of the essential types of spatial and temporal reasoning for each geoscience specialty, and an understanding of how to measure them, is established we can then proceed to developing and assessing instructional methods for supporting these skills. Targeted instructional manipulations should be investigated with the intention of assessing if and how these interventions support content learning and the development of spatial and temporal reasoning skills. A further question within this Grand Challenge is to consider whether the same instructional interventions can be used across content areas that recruit the same (or similar) spatial and temporal reasoning skills.

Some work in the Geoscience Education community has begun to investigate these questions. For example, research has demonstrated benefits for instruction that utilizes predictive sketching (Gagnier et al., 2017; Ormand et al., 2017), student produced gestural aids (Atit, Gagnier, & Shipley, 2015; Kastens, Agrawal, & Liben, 2008), embodiment and modeling (Hall-Wallace & McAuliffe, 2002; Kastens & Krumhansl, 2017; Plummer, Bower, & Liben, 2016; Woods et al., 2016), and various forms of active learning strategies (Cheek, LaDue, & Shipley, 2017; McConnell et al., 2017; Sit & Brudzinski, 2017). While the Geoscience Education community has made strides in developing and testing methods for supporting content learning and spatial and temporal reasoning, other DBER areas have laid significantly greater groundwork (e.g. Wu & Shah, 2004; Stieff, Hegarty, & Dixon, 2010; Stieff & Uttal, 2015; Augusto, 2005; Montanegro 1992,1996). Of broader relevance, Freeman et al. (2014) conducted a meta-analysis including 225 studies that compared student performance in STEM courses taught in a lecture format versus an active learning format. Encouragingly, this analysis demonstrated a strong positive effect for active learning formats, however only two of the studies included in his review were conducted in geoscience classrooms (compared to 33 biology, 31 physics, 29 math, 22 chemistry, 19 English, 14 psychology, 8 computational science). Though this was a meta-analysis of papers on active learning, there is likely a very similar need for controlled studies of temporal and spatial reasoning in the geosciences. The geoscience education community should use the research conducted in other fields to inform their own future research and should also be sure to conduct research that provides strong and reliable evidence (St. John & McNeal, 2017).

Finally, it is critical that the community make an effort to identify tasks or learning goals that are transferable and context-independent so they can be applied more widely throughout the discipline. This may extend to applying temporal and spatial skills learned within a geoscience context to other disciplines, especially as most students in introductory geoscience courses are non-majors. It is an assumption that the skills taught in those classes will be of broader applicability and therefore value to the students, but additional work is needed to support that hypothesis.

Recommended Research Strategies

1. Apply theories of attention and learning that have come out of cognitive science to more theoretically inform the instructional techniques we develop (e.g., selective attention, inhibition, cognitive capacities, principles of multimedia learning, student engagement, to name a few). For example, apply theories of selective attention to better understand why students "miss" key pieces of data during field mapping exercises.

2. Following work out of physics, identify explicit models that novices and experts rely on when completing various reasoning tasks. Use this to identify where novice reasoning goes awry and where future investigations/instructional interventions should be focused. For example, have students complete sorting tasks (e.g., in order of size or amount of time) to better understand what information they use and/or consider relevant (see example from Tinigin, Petcovic, & LaDue, 2017). This could then be compared to the information experts use to complete the same sorting task. Some specific spatial and temporal misconceptions can be found outlined by Francek (2013), Ishikawa & Kastens (2005), Kusnick (2002), and Gautier,Deutsch and Rebich (2006).

3. Study transferability from general, content-agnostic skills to discipline-specific skills and possibly vice-versa. Does training in a content-agnostic skill influence the development of a discipline-specific skill in any way?

4. Develop studies that provide strong evidence and begin to elucidate why certain techniques are effective. What are the underlying cognitive mechanisms at play?

5. An additional long term research strategy is to generate learning progressions for critical cross-cutting spatial and temporal skills. For example, how does a typical individual's ability to access temporal depth (Bluedorn, 2002) develop from the time they are a freshman to when they graduate? What are the specific learning strategies that support the development of temporal depth?

References

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

Ault, C.R. (1982). Time in geological explanations as perceived by elementary-school students. *Journal of Geological Education*, 30, 304-309.

Augusto, J.C. (2005). Temporal reasoning for decision support in medicine. *Artificial intelligence in medicine*, 33(1), 1-24.

Bluedorn, A. C. (2002). *The human organization of time: Temporal realities and experience*. Stanford, CA.: Stanford Business Books.

Cervato, C., & Frodeman, R. (2012). The Significance of Geologic Time: Cultural, Educational, and Economic Frameworks, in Kastens, K. A., & Manduca, C. A., (Eds.). *Earth & Mind II: A Synthesis of Research on Thinking & Learning in the Geosciences*. Boulder, CO:Geological Society of America, p. 19-28.

Cheek, K. A., LaDue, N. D., & Shipley, T. F. (2017). Learning About Spatial and Temporal Scale: Current Research, Psychological Processes, and Classroom Implications. *Journal of Geoscience Education,* 65(4), 455-472.

Dodick, J., & Orion, N. (2003a). Measuring student understanding of geological time. *Science Education*, 87, 708-731.

Dodick, J., & Orion, N. (2003b). Cognitive factors affecting student understanding of geological time. *Journal of Research in Science Teaching*, 40, 415-442.

Dodick, J., & Orion, N. (2006). Building an understanding of geological time: A cognitive synthesis of the “macro” and “micro” scales of time, in Manduca, C. A. & Mogk, D. W., (Eds.). *Earth and Mind: How Geologists Think and Learn about the Earth*: Denver, Geological Society of America Special Paper*,* 413, 77-93.

Dori, Y. J., & Barak, M. (2001). Virtual and physical modeling: fostering model perception and spatial understanding. *Educational Technology & Society*, 4(1), 61-74.

Francek, M. (2013). A Compilation and Review of over 500 Geoscience Misconceptions. *International Journal of Science Education*, 53.

Freeman, S., Eddy, S. L., McDonough, M., Smith, M. K., Okoroafor, N., Jordt, H., & Wenderoth, M. P., (2014). *Active learning increases student performance in science, engineering, and mathematics. Proceedings of the National Academy of Sciences*, 111(23), 8410-8415.

Gagnier, K. M., Atit, K., Ormand, C.J., & Shipley, T. F. (2017). Comprehending 3D diagrams: Sketching to support spatial reasoning. *Topics in cognitive science*, 9(4), 883-901.

Gautier, C., Deutsch, K., & Rebich, S. (2006). Misconceptions about the greenhouse effect. *Journal of Geoscience Education*, 54(3), 386-395.

Hall-Wallace, M.K., & McAuliffe, C.M. (2002). Design, implementation, and evaluation of GIS-based learning materials in an introductory geoscience course. *Journal of Geoscience Education* , 50(1), 5-14.

Hambrick, D. Z., Libarkin, J. C., Petcovic, H. L., Baker, K. M., Elkins, J., Callahan, C. N., Turner, S. P., Rench, T. & LaDue, N. D. (2011). 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.

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.

Kastens, K. A., & Ishikawa, T. (2006). Spatial thinking in the geosciences and cognitive sciences. In Maduca, C. A., & Mogk, D. (Eds.). Earth and Mind: How Geoscientists Think and Learn about the Complex Earth Learn about the Complex Earth. *Geological Society of America Special Paper,* 413, 53-76.

Kastens, K., & Krumhansl, R. (2017). Identifying Curriculum Design Patterns as a Strategy for Focusing Geoscience Education Research: A Proof of Concept Based on Teaching and Learning With Geoscience Data. *Journal of Geoscience Education*, 65(4), 373-392.

Kastens, K.A., Agrawal, S., & Liben, L.S. (2008). Research methodologies in science education: The role of gestures in geoscience teaching and learning. *Journal of Geoscience Education*, 56, 362–368.

Kastens, K. A., & Mandua, C. A. (2012). Mapping the domain of Time in Geosciences. In K. A. Kastens & C. Manduca (Eds.). *Earth & Mind II: Synthesis of Research on Thinking and Learning in the Geosciences*. Geological Society of America Special Publication. Boulder: Geological Society of America. 13-19.

Kastens, K. A., Manduca, C. A., Cervato, C., Frodeman, R., Goodwin, C., Liben, L. S., Mogk, D. W., Spangler, T. C., Stillings, N. A., & Titus, S. (2009). How geoscientists think and learn. *Eos*, Transactions American Geophysical Union, 90, 265-266.

Krantz, B., Ormand, C. & Freeman, B. (2016). 3-D Structural Interpretation: Earth, Mind, and Machine. *AAPG Memoir*, 111.

Kusnick, J. (2002). Growing pebbles and conceptual prisms–understanding the source of student misconceptions about rock formation. *Journal of Geoscience Education*, 50(1), 31-39.

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.

Manduca, C. A., & Kastens, K. A. (2012). Mapping the domain of spatial thinking in the Geosciences. In K. A. Kastens, & C. A. Manduca (Eds.). *Earth and mind II: A synthesis of research on thinking and learning in the geosciences.* Geological Society of America Special Paper, 486. Boulder, CO: Geological Society of America, 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.

Montagnero, J. (1992). The development of the diachronic perspective in children. In Macar, F., Panthas, V., & Friedman, W. J. (Eds.), *Time action and cognition*. Amsterdam: Kluwer, 55-65.

Montagnero, J. (1996). *Understanding Changes in Time*. London: Taylor & Francis.

Mosher, S., Bralower, T., Huntoon, J., Lea, P., McConnell, D., Miller, K., Ryan, J.,, Summa, L., Villalobos, J., & White, J. (2014). *Future of undergraduate geoscience education: Summary report for Summit*

on Future of Undergraduate Geoscience Education. Retrieved at http://www.jsg.utexas.edu/events/files/future_undergrad_geoscience_summit_report.pdf.

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

Ormand, C. J., Manduca, C. A., 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.

Ormand, C. J., Shipley, T. F., Tikoff, B., Dutrow, B., Goodwin, L. B., Hickson, T., Atit, K, Gagnier, K., & Resnick, I. (2017). The Spatial Thinking Workbook: A research-validated spatial skills curriculum for geology majors. *Journal of Geoscience Education*, 65(4), 423-434.

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), 143-152.

Shipp, A. J., Edwards, J. R., & Lambert, L. S. (2009). Conceptualization and measurement of temporal focus: The subjective experience of the past, present, and future. *Organizational Behavior and Human Decision Processes*, 110(1), 1-22.

Sit, S. M., & Brudzinski, M. R. (2017). Creation and assessment of an active e-learning introductory geology course. *Journal of Science Education and Technology*, 26(6), 629-645.

St. John, K., & McNeal, K. (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.

Stieff, M., Hegarty, M., & Dixon, B. (2010). Alternative strategies for spatial reasoning with diagrams. In *Diagrammatic representation and inference* (pp. 115-127). Berlin, Heidelberg: Springer.

Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement?. *Educational Psychology Review,* 27(4), 607-615.

Tarampi, M. R., Atit, K., Petcovic, H. L., Shipley, T. F., & Hegarty, M. (2016). Spatial skills in expert structural geologists. In Krantz, B., Ormand, C., & Freeman, B. (Eds.). 3-D Structural Interpretation: Earth, Mind, and Machine. *AAPG Memoir*, 111, 65–73.

Tinigin, L., Petcovic, H. & LaDue, N. (2017). How tiny is a proton? Undergraduate student familiarity with sub-meter metric scale. *Geological Society of America, Abstracts with Programs*, 49(6). *Topographic Map Assessment* developed by Matt Jacovina, Carol Ormand, Thomas F. Shipley, & Steven Weisberg.

Uttal, D. H., & Cohen, C. A. (2012). *Spatial Thinking and STEM Education: When , Why , and How? The Psychology of Learning and Motivation*, 57, Elsevier.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N.S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin,* 139(2), 352-402.

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.

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science education*, 88(3), 465-492.

Zen, E. A. (2001). What is deep time and why should anyone care? *Journal of Geoscience Education*, 49(1), 5-9.

Figures

Figure 1.
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Figure 2.
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