Design-Based Research in GIS-Infused Disciplinary Courses: Toward a Design Framework

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Abstract: Geographic information systems (GIS) is valuable as a teaching and learning tool and will play a key role in the careers of current K-12 students (NRC, 2006). However, little work has been done to understand effective approaches to integrating GIS into content instruction. In this paper, we discuss the adaptation of the Learning for Use model, a framework for the design of technology-supported, content-driven inquiry tasks (Edelson, 2001), for the context of GIS-infused content courses. Using a design-based research approach, we developed a set of design principles that reflect key elements of effective GIS-driven content instruction, which guided the adaptation of the design framework. The goal of this work is to develop a set of supports to scaffold the co-design and implementation of GIS-infused content courses that will inform a general design model of infusing GIS into content courses.

Issue addressed and potential significance

Spatial reasoning is foundational to thinking and learning across the disciplines—from biology—where students may reason about the structure and function of proteins—to civics—where they may consider how access to resources and opportunities may be unevenly distributed across their city. However, spatial reasoning is rarely explicitly taught in K-12 classrooms (NRC, 2006) and efforts to design learning environments that support its development have been limited. Such efforts may be extremely beneficial for students because spatial reasoning improves with experience (e.g., Uttal, Miller, & Newcombe, 2013).

The National Research Council's *Learning to Think Spatially* report emphasizes the value of Geographic Information Systems (GIS), a state-of-the-art geospatial visualization software, for enhancing K-12 students' spatial reasoning (NRC, 2006). Research suggests that GIS is powerful as a tool to support spatial reasoning because it enables users to create rich data visualizations and use them to reason about spatial patterns and relationships among different types of data (Bednarz et al., 2008; Bodzin, 2011). GIS is also effective as a learning tool in content instruction (e.g., Edelson, Smith, & Brown, 2008). Indeed, GIS can facilitate engagement in several of the NGSS science and engineering practices, including developing and using models, analyzing and interpreting data, and constructing explanations (NGSS, 2013). Further, GIS-infused instruction has been shown to lead to better understanding of concepts in energy, climate change, and social science compared to typical instruction in those areas (e.g., Edelson et al. 2008; Lee & Bednarz, 2009).

GIS has widespread, career-relevant applications in STEM and beyond, including law and public safety, engineering, and architecture. As a top three growth industry in technology, geospatial technologies will play an important role in the future careers of current K-12 students (U.S. Department of Labor, 2010). Given the value of GIS for supporting the development of both spatial reasoning skills and content-relevant understandings, a critical next step is to understand effective approaches for incorporating GIS into classroom instruction.

This work is part of a larger project that builds on the successful Geospatial Semester (GSS), a year-long high school course focused on developing geospatial problem-solving skills using GIS and applying those skills to local problems through extended, student-driven inquiry projects (Kolvoord, Keranen, & Rittenhouse, 2019). The main goal of the current project is to adapt the GSS design model for a new context, Chicago Public Schools (CPS). A second goal of the project is to understand the local and institutional infrastructures needed to support a sustainable model for GIS instruction in a large, urban school district, like CPS.

During the early phases of this project, we noticed tensions between the original GSS design model, an entire GIS course focused on extended, student-driven inquiry projects, and the structure of CPS courses, with content-focused instructional priorities and, consequently, limited time for GIS work. Given these competing priorities, we shifted our model towards working with teachers to strategically infuse GIS into content courses. This created the need for an explicit instructional framework that could be adapted to support lesson co-design in the context of GIS-infused content courses.

To this end, we adapted the Learning for Use (LFU) model, a framework for the design of technology-supported, content-driven inquiry tasks (Edelson, 2001). The LFU model has three main phases: motivate, construct, and refine. Motivate tasks create a demand for knowledge and elicit curiosity by revealing important gaps in students' skills and understandings. Motivate phenomena should also create the need to apply those skills and understandings to successfully complete tasks. Construct activities involve experiencing and observing phenomena using disciplinary tools for inquiry and communicating with others about those phenomena for purposes of building new knowledge. Refine lessons enable students to apply their understanding in meaningful ways and provide opportunities for metacognitive reflection. In this paper, we discuss the adaptation of this framework, guided by a set of design principles that reflect key elements of effective GIS-driven content instruction, for the current context. The goal of this work is to develop a set of supports to scaffold the co-design and implementation of GIS-infused content courses that will inform a general design model of infusing GIS into content courses.

Our methodological approach builds on models of design-based research (DBR) (e.g. Easterday, Lewis, & Gerber, 2016) by incorporating co-design and co-reflection practices, which involve ongoing collaboration among teachers, GIS mentors, and researchers, throughout the design process. Our work is additionally informed by design-based implementation research (DBIR) (e.g. Penuel, Fishman, Haugan Cheng, & Sabelli, 2011) in that, through partnerships with both teachers and district leaders, we seek to advance programs and theory related to design, learning, and implementation while developing capacity for sustaining change at the district level.

Methodological approach

Professional development workshops

We partnered with the CPS Career and Technical Education (CTE) office to identify CTE courses, including health science, business, and architecture, that involve significant spatial reasoning and could benefit from the infusion of GIS. We then incorporated other content areas, including computer science and social science, to facilitate multi-year, cross-curricular trajectories.

During the 2018-19 school year, seventeen CPS teachers across those content areas participated in six days of professional development workshops, which took place in June (3 days), August (2 days), and February (1 day). The workshops focused on building GIS technical skills using ArcGIS Online, a web-based tool. A key goal of the workshops was to develop participants' familiarity with a core set of GIS features through hands-on inquiry tasks. The workshops also incorporated support for lesson planning and implementation, including structured peer feedback routines, such as The Tuning Protocol (McDonald, Mohr, Dichter, & McDonald, 2013), small- and large-group discussions of classroom video excerpts (e.g. Sherin & van Es, 2005), and metacognitive reflections on and discussions of teachers' instructional practice. The February workshop also provided a mechanism to rapidly share preliminary, emergent design principles with the teachers and create opportunities for co-reflection around how those principles might inform practice. Throughout the workshops, teachers explored how to infuse GIS in ways that aligned with their content and context. Local GIS mentors also attended the workshops and served as an ongoing resource to teachers.

Lesson co-design

During the summer and following school year, teachers partnered with the mentors and researchers to co-design a set of GIS-infused lessons. Lessons primarily focused on GIS map building and analysis with content-relevant topics, ranging from activities that engaged students in analysis of existing maps to help understand a content-relevant phenomenon to student-driven inquiry projects in which students developed their own questions, collected or found relevant data, and used GIS to create representations and conduct analyses. For example, in a health science lesson, students collected water samples from around the city and tested the samples for a variety of pollutants. They used Survey123, a smartphone-based GIS application, to geotag and collect information about the location where the sample was collected. They then mapped the locations of the water samples and analyzed relationships between pollutant levels and demographic factors, including poverty and race. During a human geography lesson, students applied Weber's Theory of Industrial Location to determine the best place to manufacture a heart rate monitor. Students used GIS to explore relevant data layers, including shipping routes, market opportunities, and population factors, and create maps. They then conducted an analysis to determine the best location for the factory and used evidence from their maps to explain why they selected that location.

Design-based research and design principles

Using a DBR approach, we observed 28 lessons by 13 teachers at five schools. Lessons ranged from a single class period to several weeks in length. The total number of lessons implemented by each teacher ranged from one to seven. Data from the observations include field notes, lesson materials, student work, and video. Additionally, co-reflection sessions were conducted with teachers, mentors, and researchers to collaboratively generate reflections and insights on the design and implementation process and inform the development and delivery of subsequent lessons. Researchers also engaged in debriefing sessions, as suggested by Cobb et al. (2003), to gain collective insights about the classroom implementations.

During the DBR observation and debriefing process, we focused on understanding key elements of lesson design and implementation that are related to effective GIS-infused instruction. During observations, we sought to identify components of GIS-infused instruction that contribute to student engagement and learning, particularly GIS technical abilities, spatial reasoning skills, and content understandings, in this context. After each observation, memos were written to explore initial interpretations of the data and consider similarities and differences across lessons and teachers. The research team then engaged in debriefing meetings during which we examined and interpreted data from the classroom observations. In preparation for debriefing sessions, we analyzed the field notes and memos to identify themes with respect to key elements of effective lesson design and implementation. Based on this analysis, we created observation summaries, which included a description of a focal theme that emerged from the preliminary analysis and guiding questions to structure the discussion around that theme. During debriefing meetings, the research team reviewed artifacts from the classroom observation data, including classroom video segments, lesson materials, and student work. Artifacts were selected that illustrated either convergent or contrasting cases related to the focal theme. The research team analyzed these artifacts with the goal of refining the theme and generating new insights. Finally, the refined theme was connected to the literature to further inform our emergent findings and ground them in relevant prior work. Patterns of themes that emerged through this memoing, reflection, and debriefing process were then used to develop a set of design principles. The design principles reflect key components of lesson design and implementation strategies, such as classroom norms and participation structures, that are related to effective GIS-infused instruction.

For example, one debriefing session examined contrasting cases from two human geography classes with different teachers, focusing on student role. Driving questions for the debriefing session included, "To what extent are students engaging in student-driven inquiry? In what ways did aspects of the design afford or prevent that?" In the first case, the teacher provided a set of three premade maps with information about world religions, climate, and elevation. Students were given a list of religions and asked to toggle between the maps to determine how the geographical factors related to the spread of each religion. In this lesson, students were asked to use provided maps to answer a set of specific, fact-based questions and infer basic patterns related to the concept that the teacher was targeting. Students were disengaged but compliant during the lesson and, ultimately, constructed only limited understanding of both the technology and the concept.

In the second case, students were asked to use GIS to understand and explain the factors that led to any human migration in history. The teacher provided a list of possible migration topics and driving questions to guide and structure the inquiry, but students were not limited to these options. They were asked to use GIS to create three maps that were relevant to their topic of inquiry as well as a Storymap, an interactive, GIS-based presentation, explaining the causes of the migration. Students dove into exploring GIS and were able to locate relevant data and figure out the GIS functions needed to answer their questions. They were challenged and engaged by the lesson and ultimately deepened their understanding of both content and technology. At the end of the lesson, the teacher remarked that his students had even taught him new GIS functions that they had figured out on their own.

During the debriefing session, the research team analyzed classroom video segments and other relevant artifacts from each case relative to the driving questions. We noted several important contrasts between the cases. For example, the first case was heavily constrained and teacher-directed whereas the second case was much more exploratory, open-ended, and student-driven. We also noted important differences in student engagement and learning that were evident in the classroom artifacts. Based on our observations and discussion, we determined that student-driven inquiry was a key difference between the cases and, importantly, was linked to the differences in student engagement and learning we observed. We then refined the theme and connected it to the literature, which resulted in the development of a design principle. Overall, this process resulted in the development of five design principles.

Design principles analysis

We coded the 28 observed lessons for the presence of each of the design principles that resulted from the DBR process. The data was analyzed to examine the distribution and variation of these principles across lessons, teachers, and schools as well as patterns across time.

Design framework

Finally, we conducted a content analysis to map the LFU framework onto our context, guided by the design principles. This mapping process involved identifying correspondences between the principles and the phases of the framework and articulating how these principles would translate into the design of GIS-driven activities that align with each phase. We additionally defined the components that need to be included and criteria that need to be met by activities in each phase. This process resulted in an adaptation of the LFU framework for our context of GIS-infused content instruction.

Findings

Design principles

Five design principles emerged from the DBR observation and debriefing process: (1) student-driven inquiry, (2) culturally responsive instruction, (3) foregrounding spatial reasoning, (4) connecting to disciplinary content, and (5) creating a collaborative community of learners. These design principles reflect key elements of lesson design and implementation that are related to effective GIS-infused instruction. The principles build on the foundational work they reference by articulating how the principle is instantiated in our GIS-driven instructional context. (1) Drawing from learner-centered design (Bransford, Brown, & Cocking, 1999), student-driven inquiry in this context involves students taking the lead in learning GIS through "guided discovery". This involves students choosing their own questions, exploring the GIS functions and analyses they need to answer those questions, and figuring out how to use them. Teachers can provide constraints, such as vetted topics or data options, to scaffold this process. (2) Culturally responsive instruction is grounded in and relevant to students' lives and community cultures (Ladson-Billings, 1995; Lee, 2004) and leverages students' funds of knowledge (e.g. González, Moll, & Amanti, 2006). In this context, lessons should incorporate GIS in ways that connect content to students' lives, experiences, and communities, creating connections between content-relevant issues and prior knowledge. (3) Foregrounding spatial reasoning with GIS involves creating opportunities for students to reason about why things are where they are and why that matters for the topic they are investigating (e.g., Uttal, Miller, & Newcombe, 2013). Such lessons go beyond creating informational maps, focusing instead on using maps to analyze spatial patterns and reason about how they inform content-relevant understandings. (4) GIS-infused lessons should also be rooted in and deeply connected to disciplinary content (e.g. Mishra & Koehler, 2006). This involves using GIS to investigate topics, including course-relevant models and concepts, that enable students to build or deepen course-relevant understandings, rather than learning GIS technical skills in isolation. (5) Finally, GIS lessons can be challenging in that they involve learning new habits of mind while navigating unfamiliar, complex technology and, as such, should be situated in a collaborative community of learners (e.g. Brown & Campione, 1994). This involves creating a culture of safety, in which errors are framed as productive learning opportunities, and normalizing the struggle of learning GIS. Teachers should be positioned as a "guide on the side" who is working to figure out GIS alongside the students (King, 1993).

Design principles analysis

Across the 28 observed lessons, there was variation in the extent to which each of the design principles was reflected in the lesson. Overall, most of the lessons were connected to disciplinary content (90% of lessons) and engaged students in spatial reasoning (61%). During many lessons, teachers and students also fostered a culture of safety and collaboration, with 48% of lessons reflecting this design principle. However, student-driven inquiry (32%) and culturally responsive instruction (35%) were less commonly reflected in the data. These two principles are critical for the design of learning environments that engage students in inquiry around local problems of interest, a key goal of our work, but necessitate a departure from traditional forms of instruction.

As illustrated in figure 1, there were also important differences with respect to how many of the design principles were incorporated across lessons, teachers, and schools. The presence of more design principles suggests increasing alignment with our design model for GIS-infused content instruction. Some lessons did not reflect any of the design principles, while others incorporated all five principles. For some teachers there was variation from lesson to lesson, which may have been driven by differences in topic and lesson goals, while other teachers incorporated the same number of principles across lessons. All three teachers at school A showed an increase in the number of design principles reflected across lessons. This suggests improvement in their lesson design and implementation practices over time, moving towards instruction that is increasingly aligned with the design model.

Design framework

The initial course design framework emerged from our analysis of the first year of co-designed GIS-infused lessons. It was developed by integrating our five design principles into the LFU model. The goal of the design framework is to provide detailed guidance and constraints to support the design of GIS-infused content courses. Overall, the framework moves from motivate activities, which foster curiosity and create demand for GIS through real world experiences that demonstrate the power of the technology, through construct tasks, which engage

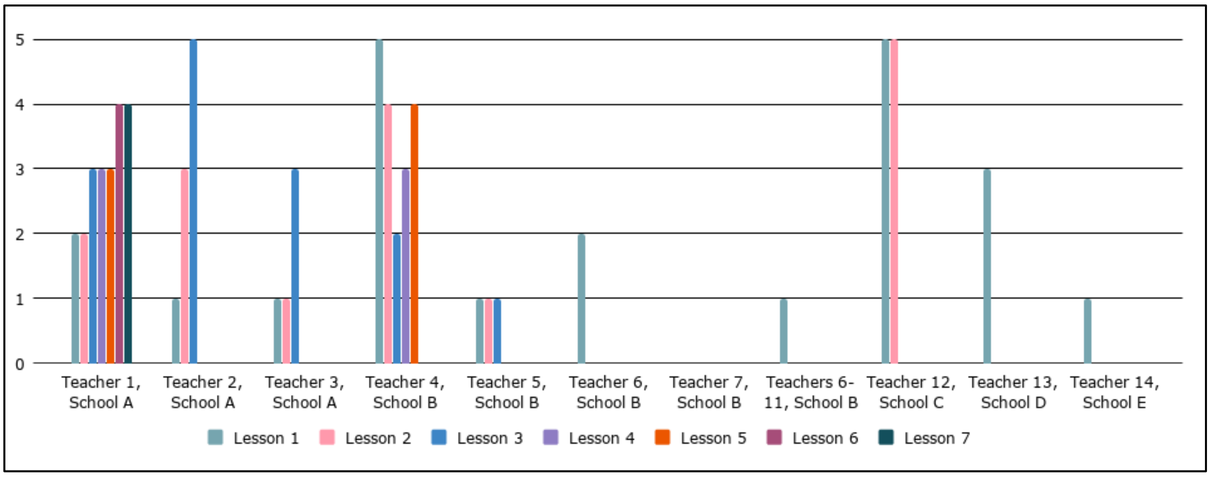

Figure 1. Number of design principles by lesson, teacher, and school.

students in content-relevant sense-making and analysis with maps. As students build skills and understandings, their role progressively increases towards generating questions, finding or collecting relevant data, and creating maps. During the refine stage, students apply their knowledge in student-driven inquiry projects. This motivate, construct, refine sequence applies not only to the design of the course, as detailed below, but also within a given lesson. The five design principles are all relevant across the entire course, but principles that play a key role at each stage are highlighted below.

Motivate activities comprise the first few lessons in the course. The purpose of these lessons is to create a demand for GIS as a tool and foster students' curiosity about course-relevant phenomena that can be better understood through GIS. The first recommended activity involves collecting local data that is both course relevant and connected to a topic that students know and care about and using this data to create and analyze a simple map. During the motivate phase, students also explore and make sense of a professional GIS map that is engaging and impressive as well as course-relevant to understand the power and potential of GIS. With respect to design principles, culturally responsive instruction is critical to the design of motivate activities. A central goal of these tasks is to build purpose around GIS as a tool that can help students investigate and understand problems that are relevant to their lives and communities. Additionally, building a collaborative community of learners is a key focus of the motivate stage as teachers work to establish norms around the culture of safety and collaboration in which GIS learning occurs.

Construct tasks, which involve creating and analyzing course-relevant maps and using those maps to generate explanations, make up the bulk of the GIS lessons in a year-long GIS-infused content course. Construct tasks are meaningfully and strategically integrated into content instruction during units where GIS can enhance understanding of course-relevant concepts and models. Relevant background information is provided through texts and lectures. Small- and large-group discussions are included to support sense-making with the maps and background information. Peer feedback, presentation, and discussion routines are incorporated throughout the construct phase to support collaboration and advance students' skills and understandings. Importantly, these tasks start simple and progressively build the complexity of maps, questions, and student roles while decreasing scaffolding. Rather than front loading technology, GIS technical skills and analyses are incorporated as needed for each lesson. In early construct tasks, teachers provide the questions and data and the class collaboratively analyzes the maps. Next, teachers provide candidate questions and vetted data options and enable students to choose from those options and conduct the analysis. As they develop their skills, students begin working with the teacher and one another to generate questions, find or collect data, and analyze the maps that they create. Throughout the year, the class collects and records inquiry questions that students generate during these construct lessons to get students thinking about GIS- and content-relevant topics that they may be interested in investigating. With respect to design principles, foregrounding spatial reasoning and connecting to disciplinary content are key to the design of construct activities. As student role increases over time, student-driven inquiry is also layered into these tasks. Throughout the construct phase, teachers and students continue to build their collaborative community of learners as technological roadblocks are used as productive learning opportunities to advance everyone's understanding of GIS.

The refine phase is the culmination of the course. Students apply their skills and understandings to extended student-driven inquiry projects. During these projects, students generate their own questions, often focusing on local issues that they know and care about. This enables students to draw on their funds of knowledge along with the GIS and spatial reasoning skills they have developed. Students find or collect data that is relevant to their question, create representations, and conduct analysis to understand and explain the issues they are investigating. Finally, projects are presented to and discussed with fellow students and community members to share findings, reflect on what has been learned, and, potentially, effect change in the community. At the core of these inquiry projects are the design principles of student-driven inquiry, culturally responsive instruction, and spatial reasoning. Additionally, the work that teachers and students have done to establish their collaborative community of learners sets the stage for the independent but supported discovery that occurs during this phase.

Conclusions and implications

The design framework and principles were introduced to new and continuing teachers at the beginning of the 2nd year workshops as teachers began redesigns of their GIS-infused courses. Teachers, mentors, and researchers are currently applying these supports to iteratively redesign existing lessons and co-design new lessons. They are also co-designing course maps that lay out a year-long sequence of GIS-infused lessons that aligns with the GIS-based LFU framework. The course maps pinpoint which units those lessons align with in their course. Teachers are currently implementing their refined lessons and we are continuing to observe and analyze this work using a DBR approach. In our future work, we will explore how teachers' 2nd year lesson designs and implementation have shifted in light of the GIS-based design framework.

The goal of this ongoing co-design work is to develop year-long, GIS-infused content courses. We are working with the CTE office in CPS to review the course maps and lessons for consideration to become part of the official CTE curriculum for the targeted career pathways. The next phase of work will entail the development of teacher leaders who can train new teachers, creating a sustainable model for GIS-infused instruction across the district.

References

Bednarz, S. W, Chalkley, B., Fletcher, S., Hay, I., Heron, E. L., Mohan, A., & Trafford, J. (2008). Community engagement for student learning in geography. *Journal of Geography in Higher Education, 32*(1), 87-100.

Bodzin, A. M. (2011). The implementation of a geospatial information technology (GIT)-supported land use change curriculum with urban middle school learners to promote spatial thinking. *Journal of Research in Science Teaching, 48*(3), 281-300.

Brown, A. L., & Campione, J. C. (1994). *Guided Discovery in a Community of Learners*. Cambridge, MA: The MIT Press.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design Experiments in Educational Research. *Educational Researcher, 32*(1), 9-13. http://edr.sagepub.com/content/32/1/9.abstract. doi: 10.3102/0013189x032001009

Easterday, M. W., Lewis, D. G. R., & Gerber, E. M. (2016). The logic of the theoretical and practical products of design research. *Australasian Journal of Educational Technology, 32*(4).

Edelson, D.C. (2001). Learning-for-Use: A framework for the design of technology-supported inquiry activities. *Journal of Research in Science Teaching, 38*(3), 355-385.

Edelson, D. C., Smith, D. A., & Brown, M. (2008). Beyond interactive mapping: Bringing data analysis with GIS into the social studies classroom. *Digital geography: Geospatial technologies in the social studies classroom*, 77-98.

Fishman, B. J., Penuel, W., Allen, A., Cheng, B., & Sabelli, N. (2013). Design-based implementation research: An emerging model for transforming the relationship of research and practice. *National society for the study of education, 112*(2), 136-156.

González, N., Moll, L. C., & Amanti, C. (Eds.). (2006). *Funds of knowledge: Theorizing practices in households, communities, and classrooms*. Routledge.

King, A. (1993). From sage on the stage to guide on the side. *College teaching, 41*(1), 30-35.

Kolvoord, B., Keranen, K. & Rittenhouse, P. (2019). The geospatial semester: Concurrent enrollment in geospatial technologies. *Journal of Geography*, *18* (1), pp. 3-10.

Lee, C. D. (2004). Bridging home and school literacies: Models for culturally responsive teaching, a case for African-American English. *Handbook of research on teaching literacy through the communicative and visual arts*, 335-345.

Lee, J., & Bednarz, R. (2009). Effect of GIS learning on spatial thinking. *Journal of Geography in Higher Education, 33*(2), 183-198.

McDonald, J. P., Mohr, N., Dichter, A., & McDonald, E. C. (2013). *The power of protocols: An educator's guide to better practice*. Teachers College Press.
Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, *108*(6), 1017-1054.
NGSS Lead States (2013). *Next generation science standards: For states, by states.* Washington, DC: The National Academies Press.
National Research Council. (2006). *Learning to think spatially: GIS as a support system in the K-12 curriculum*. Washington, DC: National Academies Press.
Penuel, W. R., Fishman, B. J., Haugan Cheng, B., & Sabelli, N. (2011). Organizing research and development at the intersection of learning, implementation, and design. *Educational researcher, 40*(7), 331-337.
Sherin, M., & van Es, E. (2005). Using video to support teachers' ability to notice classroom interactions. *Journal of technology and teacher education, 13*(3), 475-491.
Uttal, D. H., Miller, D. I., & Newcombe, N. S. (2013). Exploring and enhancing spatial thinking: Links to achievement in science, technology, engineering, and mathematics? Current Directions in Psychological Science, 22(5), 367-373.
Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. Journal of Educational Psychology, 101(4), 817-835.

Acknowledgements

The research reported here was supported by the National Science Foundation through grant 1759360.