A Research Agenda for Geospatial Technologies and Learning

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ABSTRACT

Knowledge around geospatial technologies and learning remains sparse, inconsistent, and overly anecdotal. Studies are needed that are better structured; more systematic and replicable; attentive to progress and findings in the cognate fields of science, technology, engineering, and math education; and coordinated for multidisciplinary approaches. A proposed agenda is designed to frame the next generation of research in this field, organized around four foci: (1) connections between GST and geospatial thinking; (2) learning GST; (3) curriculum and student learning through GST; and (4) educators' professional development with GST. Recommendations for advancing this agenda are included.

Key Words: *GIS, instructional activities, learning, pedagogy, geospatial thinking*

Tom R. Baker is an education manager at Esri, and an adjunct faculty member at the University of Kansas, Lawrence, Kansas, USA.

Sarah Battersby is an associate professor of geography at the University of South Carolina, Columbia, South Carolina, USA.

Sarah W. Bednarz is a professor of geography at Texas A&M University, College Station, Texas, USA.

Alec M. Bodzin is a professor in the teaching, learning, and technology program at Lehigh University, Bethlehem, Pennsylvania, USA.

Bob Kolvoord is the dean of the College of Integrated Science and Engineering at James Madison University, Harrisonburg, Virginia, USA.

Steven Moore is director of the Center for Spatial Studies at the University of Redlands, Redlands, California, USA.

Diana Sinton is the executive director of the University Consortium for Geographic Information Science, and an adjunct professor of GIS at Cornell University, Ithaca, New York, USA.

David Uttal is a professor of psychology and of education at Northwestern University, Evanston, Illinois, USA.

INTRODUCTION

Geographic information systems (GIS), remote sensing (RS), global positioning systems (GPS), and digital globes comprise the four core geospatial technologies (GST). The potential for these technologies in precollegiate teaching, learning, and problem solving has long been advocated (e.g., National Research Council 2006; Goodchild and Janelle 2010). Each has been used in a variety of settings and with a range of learners, but the lack of detailed, research-based evidence for sustained benefits of GST to learning is one hindrance of large-scale implementation. Existing research in this area has been sparse and fragmented, with no clear plan to provide guidance to aspiring investigators (Baker and Bednarz 2003; Baker *et al.* 2012). Studies have offered tantalizing glimpses at the affordances of GST, but they are rarely replicated or brought to scale. This limitation was recognized recently when the National Science Foundation (NSF) funded the *Road Map for Large-Scale Improvement of K–12 Geography Education.* The Geography Education Research Committee (Bednarz, Heffron, and Hunyh 2013) concluded that education research in geography and related fields that use GST needs to be better structured, more systematic, attentive to progress and findings in cognate fields of science, technology, engineering, and math (STEM) education, and coordinated for multidisciplinary approaches. Confirming these recommendations, the GST community put forth a call that explicitly noted the need to develop a research agenda to help provide a roadmap to direct research in the area (Baker *et al.* 2012). This article responds to that call.

A research agenda focused on GST and learning is needed to highlight existing knowledge gaps, encourage engagement from broad-based scholarly teams, and inform new audiences about this rich research area. To address and clarify the issues that have previously limited effective research on GST and learning, we, a group of researchers with varied backgrounds and experience in this area, propose an agenda to frame and advance the discussion of potential avenues of study. Collectively our group includes university faculty and industry members from different content discipline areas, with research expertise in spatial cognition and GST curriculum design and development. The multiple perspectives we represent allow us to consider teaching and learning about and with GST broadly and to consider multidisciplinary approaches that are necessary to move GST research forward.

The full domain of GST and learning within formal and informal educational settings involves a myriad of variables, stakeholders, content areas, and dependencies, including spatial thinking, defined as a set of abilities to visualize and interpret spatial concepts and geospatial thinking, a specialized form of spatial thinking focusing on patterns and processes that take place on or near the earth's surface, and at the scale of human experiences. Multiple technologies, pedagogy, and content knowledge are also contributing variables. Given these factors and their interactions, the opportunities for educational research are rich and demanding, and a well-organized and well-justified agenda is needed to enable significant progress. As an essential first step, we identify guiding and foundational research principles. The historical absence of such structure has contributed to the poor state of knowledge around GST and learning, particularly from the perspective of geography education research. Next, we identify the four key research foci that frame our proposed agenda: (1) connections between GST and geospatial thinking; (2) learning GST; (3) professional development with GST; and (4) curriculum and student learning through GST. Each of these are

discussed in detail, with highlights of existing research and suggestions for the types of research questions that could next be posed. We also discuss the issues of research design and assessment as it applies to GST and learning, as these have been underdeveloped in the past. We conclude with recommendations to advance this research agenda.

GUIDING PRINCIPLES FOR A RESEARCH AGENDA ON GST AND LEARNING

Drawing from expert guidance (National Research Council 2002), and supplementing from our own collective professional experiences, we began by identifying foundational principles that are needed to realize high caliber research around GST and learning. The framework is deliberately broad because a failure to observe one or more of these principles has contributed to suboptimal outcomes in the past, whether that means results that are uninteresting, unreplicable, overly anecdotal, inaccessible to or unknown by interested scholars in cognate disciplines, or impossible to implement or apply. Thus we grounded our research agenda around a series of guiding principles, detailed below.

Design and Plan for Sound Educational Research

In 2002 the National Research Council (NRC) prepared a report on the practices of scientific education research in an effort to elevate their output and quality. This report stated that research should focus on significant questions, be designed to build coherent explanations and explicit chains of reasoning, and be replicated and generalized across studies (National Research Council 2002). Unfortunately, a significant amount of research conducted in the past has not met these standards, and that has brought us to where we are today. We concur with the recommendations of this NRC report and further emphasize that GST and learning research may wish to draw from the framework we have proposed here to seek to maximize the likelihood of acceptance, recognition, and implementation, particularly when policy decisions are in question.

Recognize That a Range of Research Types and Approaches Are Needed

The NRC called for educational research that was sound and robust but avoided specifying or recommending any one type of research methodology over another. In the domain of GST and learning, basic research is needed that focuses on developing education practices (foundational, early-stage, or exploratory, and design and development studies), as well as studies that assess the broad impact of education interventions and strategies (Institute of Education Sciences and National Science Foundation 2013). Both basic and applied research are critical to develop best educational practices. Therefore, we advocate the need to develop fundamental understandings and assessments of spatial abilities as well as measurements of learning outcomes and goals across the domain of geospatial

thinking, learning, and use of GST. The assessments may require novel instruments that operate in and provide feedback in near real-time. The approach of design-based implementation research that is meant to be iterative, collaborative, and built from the "persistent problems of practice from multiple stakeholders' perspectives" (Penuel *et al.* 2011, 332) may be an ideal match for classroom-based inquiry involving GST. Furthermore, a research agenda must also extend beyond the classroom to teachers as adult learners of and with GST, for their professional development needs must also be understood and met to increase the likelihood of effective GST learning experiences by students.

Address Contemporary, Current Educational Concerns

Concurrently, recommendations for research in GST and learning should align with, address, and complement the standards and priorities recognized by broader educational constituencies. For example, currently there is interest in the practices of interpretation and communication of data across disciplines. Recent revisions to the National Geography Standards include expectations that geospatial technologies be used to help students "understand and communicate information" (Geography Standard 1). Similarly, competent use of data also figures prominently in the Next Generation Science Standards (NGSS Lead States 2013). Moreover, the new Common Core State Standards, under which more than 42 million K–12 students and teachers in the United States are operating, stresses *informational texts* accompanied by maps, graphs, tables, charts, and figures (National Governors Association Center for Best Practices and Council of Chief State School Officers 2010). Attention to these recent education reform documents, and others of contemporary interest, should be included in any GST research agenda. Aligning research with current and ongoing activities and policies will increase opportunities for scholars to engage in meaningful, authentic learning environments.

Build From and Design for Multidisciplinary Teams

In order to build capacity in GST education research, collaborations among a range of disciplines—including the learning, natural, social, and cognitive sciences—must be developed. Single content domain research often fails to adequately address the necessary range of pedagogical, technical, and content knowledge most often associated with GST and learning. For example, in a typical study that examines how students use a GIS to explore a history topic, the existence of confounding variables including how the teacher delivers instructions, or how the data are represented online, can influence students' learning outcomes. Without research that adequately addresses all of these issues, we limit the integration and implementation of research-based evidence into classroom practices.

Shifting to multidisciplinary research teams may produce more robust research designs and outcomes, but this shift

Table 1. Key terms and phrases relevant for multidisciplinary conversations about GST and learning.

Term or Phrase	Definition	Relevant References
Spatial thinking	A set of abilities to visualize and interpret location, position, distance, direction, relationships, movement, and change through space. *Spatial thinking and reasoning* involve cognitive processing of spatial data. This locational, positional, and measurement data is encoded and stored in memory, and can be represented externally by visualizations.	Sinton 2011; Sinton *et al.* 2013; Uttal 2000
Geospatial thinking	A specialized form of spatial thinking that is bound by Earth, landscape, and environmental scales. *Geospatial reasoning skills* are higher-order cognitive processes that provide a means to manipulate, interpret, and explain information, solve problems or make decisions at geographic scales.	Bodzin *et al.* 2014
Fidelity of implementation	Identifying the critical components of the curriculum innovation and determining if they are present during enactment in the instructional setting.	Mowbray *et al.* 2003
Efficacy design studies	Studies that allow for testing of a strategy or intervention under *ideal* circumstances, including a higher level of support or developer involvement than would be the case under normal circumstances	Institute of Education Sciences and National Science Foundation 2013.
Design-based implementation research	Research that focuses on implementation, both in the development and initial testing of interventions and in the scaling-up process with the aim of investigating and improving the effective implementation of interventions.	Penuel and Fishman 2012

Note: GST = geospatial technologies.

also introduces terms and ideas that have discipline-specific connotations, a fact that hinders effective cross-disciplinary communication. To avoid ambiguity, we have defined key terms as they are operationalized in our agenda (Table 1). Though it is neither realistic nor practical to enforce singular definitions and terminology across disciplines, until we explain such terms and their applied usage, we will continue to hinder the multidisciplinary conversations we want to foster.

Engage Both Formal and Informal Learning Environments

As the use of GST slowly expands to diverse learning settings, both formal and informal, we are aware that conducting research studies within authentic K–12 learning environments is challenging. The constraints of the real world of the classroom often stand in opposition to laboratory research practice. These barriers, real or perceived, should be recognized early in the research design process, and incentives must be put in place to effectively bridge the research and practice divide. For example, incorporating outcomes into the research design that are of high value to teachers and administrators, such as materials that are well-correlated with subject standards and likely to have positive impacts on high-stakes testing, is a strategy to create high-profile research opportunities. At the same time, activities involving GST are already more common in informal learning settings, and leveraging these for research

may enable more rapid and flexible research projects. For example, geocaching is a merit badge activity in scouting and is also popular in afterschool clubs and could be used as the basis for a GST and mapping study.

THE GST AND LEARNING AGENDA

A research agenda addressing such broad and rich areas of inquiry requires an organizational framework. We designed four research categories that place broad questions into subfields, and reflect focused themes that have emerged in the past (e.g., Baker and Bednarz 2003). While these categories will inevitably and naturally ebb and flow with changes in education, cognitive theory, and technology, they present a cogent framework for understanding. For each one, we also offer examples of specific research questions that each category might engender (see Tables 2–5). This approach allows us to identify the important distinctions of a category though we realize that in practice it is likely, valid, and necessary for lines of inquiry to cross category boundaries.

Connections between GST and Geospatial Thinking

Known and envisioned relationships between geospatial technologies and geospatial thinking may be the most fundamental to investigate (National Research Council 2006). Though we are focusing on *geospatial thinking* in this agenda, its connections with the broader concept of *spatial*

thinking are essential to appreciate (see Table 1), particularly because the use of GST often involves both geospatial and spatial thinking, concurrently. We suggest that the relation between GST and geospatial thinking is reciprocal in nature. On one hand, basic skills such as defining a problem, posing potential solutions, and interpreting results (Bednarz and Bednarz 2008) are prerequisite skills for the use of GST to solve spatial problems. How well students solve problems across geographic space at different scales, or the extent to which students can transfer their skills from navigating within virtual gaming worlds to navigating with a virtual globe of real geographic space are examples of applied geospatial thinking skills. At this point, we know little of what skills are most relevant or necessary to enhance or develop geospatial thinking skills, nor do we know how varying levels of background knowledge impact the ability to enhance or develop such skills in the first place.

On the other hand, the activity of using GST greatly influences how people think about geospatial information. Maps, charts, graphs, and other geospatial representations bring into view information that would be difficult, if not impossible, to acquire from direct experience in the world. GST facilitates data collection, visualization of spatial relationships, analysis, and filtering or querying of geospatial data, all activities that can be of use in making sense of spatial data and patterns. Learning to think about the world through the mediated perspective that technologies provide may affect geospatial thinking and its development (e.g., Uttal 2000, 2005; Liben, Myers, and Kastens 2008). Numerous researchers have suggested that use of GST for this type of activity can help improve students' spatial thinking abilities (e.g., Albert and Golledge 1999; Hall-Wallace and McAuliffe 2002; National Research Council 2006). However, empirical research in this area has been limited and of a narrow nature, such as a study that focuses on a single class or a one-time GST activity. For example, Marsh, Golledge, and Battersby (2009) found that sixth grade, high school, and college students all struggled with understanding particular spatial concepts that would inform effective GIS use, but such findings have neither been investigated further nor replicated with other students or concepts.

The absence of validated instruments to assess geospatial thinking is a barrier to advancing research around GST and geospatial thinking. Effective evaluation instruments will be able to differentiate between testing students' ability to use GST software correctly and their ability to think geospatially (cf. Marsh, Golledge, and Battersby 2009; Bodzin *et al.* 2014). It is one thing to be able to successfully perform analyses with GST, and entirely another to understand *what* the appropriate analysis method is, *why* it should be used, *how* the results help in understanding a spatial process or pattern, *when* or *how* the same type of spatial analysis could be used in situations without technological support, and whether improvement in spatial thinking ability is actually connected to GST use or other factors. This important topic is discussed further below.

Investigating the relationships between the broad topics of GST and geospatial thinking will require attention to many factors and variables (Table 2). These could include the complexity of GST and its applicability to individual geospatial thinking tasks; the usability of the technology for individual students (by age, grade, or developmental level of the learner); the nature of the learning activity; and the relationships between spatial abilities and geospatial thinking. Especially with classroom-based research, conscientious alignment of GST with defined learning outcomes needs to be demonstrated. Even a well-designed GST activity will be ineffective if it is not appropriate for the learning topic, a result that will further undermine efforts to implement the use of GST in classrooms. Emerging understanding of learning progressions (National Research Council 2007) may help guide investigations on how learners' geospatial thinking evolves over time while a using GST-infused curriculum. The development of a learning progression for geospatial thinking would include an ordering of geospatial concepts that builds toward more sophisticated geospatial understandings and reasoning skills, while providing learning strategies and learning experiences to support student development along the progression. Assessment measures to define students' progress on the learning progression will also need to be included (Huynh, Solem, and Bednarz forthcoming).

Learning about GST

The second key research focus is on learning about GST. Learning *about* GIS software is distinct from learning about other topics *with* or *through* GIS. This distinction has long been noted (Sui 1995), and continues to be relevant for educational researchers. Both the learning goals (academic-content-oriented versus technical-skill-oriented) and the learning activities of these two approaches are necessarily different. Learning *with* GIS relies on limited interaction with software in order to focus on subject-area content through problem- or inquiry-based learning. How technology affects the learning of academic content is a fairly well-studied phenomenon, especially among the STEM disciplines (e.g., Lee *et al.* 2010). In contrast, the primary goal of learning *about* GIS is for learners to effectively and responsibly operate the software, frequently with supporting instruction in cartography, database design, and programming. While such goals are common in higher education and professional development, in K–12 education these goals are uncommon outside career and technical education (CTE) programs. Only very few specialized programs exist otherwise (e.g., the Virginia Geospatial Semester, and the Environmental and Spatial Technologies (EAST) program).

As a field itself, geographic information science has only recently had its knowledge, skills, and practices defined and described (DiBiase *et al.* 2006; DOLETA 2010). These efforts were intended for higher education and workforce audiences, with little direct attention paid to precollegiate educators. To address the occasional inclusion of GIS

Table 2. Research questions pertaining to GST and geospatial thinking.

Each of these is designed as an example of the type of question that could be posed by a researcher interested in this category of GST and learning research. This list is not intended to be either comprehensive or exhaustive.	
1. Do geospatial technologies facilitate geospatial thinking and reasoning, and if so, how?	a. How can we creatively and convergently measure changes in students' spatial thinking skills following the use of geospatial technologies? (e.g., gesture, vocabulary, authentic tasks, etc.)
	b. Are there scale dependencies where geospatial technologies are more or less successful at facilitating geospatial thinking and reasoning? When does the technology become *necessary* for solving certain geospatial problems, as the geographic component is too large, or the problem too complex to solve without technological aid?
	c. Do some geospatial technologies serve as a "crutch" to limit the need for reliance on the cognitive component of spatial thinking? If so, in what situations and why?
	d. How does the effectiveness of geospatial technologies for facilitating spatial thinking and reasoning vary based on age/grade/developmental level, technological complexity, and learning or teaching method?
	e. What are examples of best practices for successful teaching with geospatial technologies to facilitate development of geospatial thinking and reasoning habits of mind?
2. How does geospatial thinking facilitate the ability to use geospatial technologies?	a. How does spatial problem solving with GIS and other geospatial technologies relate to traditional (psychometric) spatial abilities?
	b. How does prior experience in spatial problem solving influence the learning of new geospatial technologies?
	c. How do geospatial skills develop and how do they differ in children of different ages? How does this inform the understanding or use of geospatial technologies?
3. What factors affect geospatial learning and can influence the impact of geospatial technologies to promote learning?	a. What are the connections between spatial thinking, as typically studied by psychologists as spatial abilities, and geospatial thinking?
	b. How could geospatial thinking habits of mind be operationalized? What are these habits of mind? What are their indicators? How do they develop? What are the roles of geospatial technology in enabling and supporting them?
	c. What roles do movement, gesture, and verbal expression play in priming elementary children's brains to understand spatial relationships and concepts in later grades?

Note: GST = geospatial technologies; GIS = geographic information systems.

in CTE state standards (e.g., Kansas, Florida, Virginia), teachers are left to modify the instructional sequences and range of content used in higher education or professional training programs, or rely on tutorial books designed by commercial software companies for K–12 audiences. No published research exists on how effective learning is in these situations.

In fact, we have little information or guidance on best practices for how younger students learn GIS and other GST, and this leaves many areas open for research (Table 3). Some scholars suggest that GST learning benefits from informed sequencing of content (Howarth and Sinton 2011), while other studies indicate that software use should only follow traditional instruction of certain spatial principles (Golledge, Marsh, and Battersby 2008; Marsh, Golledge, and Battersby 2009). Yet empirical research to support these ideas is limited in scope and scale. Within research that involves student use of software, scholars have focused on spatial thinking skills (Nielson, Oberle, and Sugumaran 2011) or map interpretation skills (Shin 2006) as learning outcomes, rather than the acquisition of GST knowledge

itself. Meanwhile, an emerging area for research is how Web-based delivery platforms affect learning (Milson and Earle 2007; Songer 2010), important questions given the move towards cloud-based GST technologies, and yet another factor to be considered.

Professional Development and GST

Understanding how GST learning happens for students is closely aligned with the next category, how teachers learn GST through professional development (PD). Within this area, educational researchers have been more active overall. In localized PD settings, investigators have reported that individualized teacher support, use of local data and localized problem scenarios, and administrative commitment, have been critical to GST professional development (see McClurg and Buss 2007; Penuel *et al.* 2007; Baker, Palmer, and Kerski 2009; Trautmann and MaKinster 2010, 2014; Moore *et al.* 2014). Curriculum materials can be designed to influence teacher decision making by conveying instructional practices, providing appropriate content materials, or providing pedagogical implementation ideas (Davis and Krajcik 2005;

Table 3. Research questions pertaining to learning GST by precollegiate students.

Each of these is designed as an example of the type of question that could be posed by a researcher interested in this category of GST and learning research. This list is not intended to be either comprehensive or exhaustive.

1. Is there an optimal sequence of content, skills, or technology tools to learn GST?
   a. What are the appropriate skills to be considered?
   b. How does the optimal sequence vary with different learners, contexts, or GSTs themselves?
   c. Are there specific instructional models, sequences, or scaffolding support associated with optimal learning sequences?
   d. What strategies can accelerate learning fundamental GST skills, thereby allowing learners to spend more instructional time on geospatial data analysis and visualization?
   e. Is there a collection of pre-GIS skills, based in spatial concepts, that would facilitate GIS learning?
2. What factors or variables affect the learning of GST?
   a. How do learners with individual differences (such as learning disabilities, sight-impairment, English-language learners) learn GST? What instructional supports are needed?
   b. How does the context of use impact learning about GST?
   c. Can GST-based "problems" be organized, sequenced, or distilled into constituent parts to facilitate more effective or transferable GST skills?
3. How does learning to use GST inform or develop geospatial thinking?

Note: GST = geospatial technologies; GIS = geographic information systems.

Davis and Varma 2008). PD that integrates GST within curriculum materials that are educative for teachers (Davis and Krajcik 2005) have been found to support science teachers' professional growth related to their geospatial science pedagogical content knowledge during curriculum enactment (Bodzin, Peffer, and Kulo 2012; Kubitskey *et al.* 2014).

However, the existing literature base on PD with GST documents primarily small-scale efficacy design studies that have investigated PD implementation over extended periods of time with ongoing technological support, hybrid models of online and face-to-face learning, and curricular flexibility (Moore *et al.* 2014; Trautmann and MaKinster 2014). Peer coaching, practice teaching with students, and developing coherence with district educational goals and teachers' personal PD goals have also been shown to be effective tactics (Penuel *et al.* 2007; Conover, Kermish-Allen, and Snyder 2014; Stylinski and Doty 2014), as is having the content be relevant for students (Coulter 2014), but again, in small-scale studies with limited implementation opportunities. As is often the case, more and larger-scale efficacy studies are needed to determine the effectiveness of these practices, including research to uncover how the efficacy of each practice varies across different content areas, teacher experience with GST, grade levels, and student populations; and examine how research-based PD in GST applied to disciplinary-based content areas can best impact student learning. Possible specific questions are noted in Table 4.

Furthermore, successful use of GST in education requires that teachers have a strong understanding of relevant content knowledge, geospatial software applications, data analysis techniques, and pedagogical implementation strategies that meet the needs of students (Coulter 2014).

Some teachers have not had adequate or effective PD experiences to combine these skills and knowledge and therefore fall short when they attempt to implement curricula that use GST to promote core content learning and the development of geospatial thinking skills (Bodzin, Peffer, and Kulo 2012). Comprehensive PD frameworks that take into account a full range of technological, pedagogical, and content knowledge (TPCK) (Mishra and Koehler 2006; Koehler and Mishra 2009) are a logical place to start. Peffer, Bodzin, and Kulo (2010) added geospatial science and created the GS-TPCK; originally designed for science instructors, its framework can easily be modified for other core disciplines where instruction with GST is likely to be found, such as the social sciences. More research in the field is needed to investigate how to use frameworks such as TPCK in different professional development models, and to examine which teacher learning experiences may best support their use of GST with students.

Curriculum and Student Learning with GST

The fourth research category identifies key research questions related to curriculum design, implementation, and student learning *with* or *through* GST (versus learning *about* GST, discussed earlier). Little of the current K–12 classroom-based GST use is in the form of a coherent, disciplinary-based, GIS-integrated curriculum that facilitates empirical research on either content learning or geospatial thinking skills (Barnett *et al.* 2010). Published research studies have typically been exploratory, smaller-scale efficacy studies associated with GST-supported curricula ranging from a few learning activities to a few weeks' worth of implementation (Hall-Wallace and McAuliffe 2002; Baker and White 2003; Kerski 2003; Patterson, Reeve, and Page 2003;

Table 4. Research questions related to professional development and policy with regard to the use of geospatial technologies (GST) in education.

Each of these is designed as an example of the type of question that could be posed by a researcher interested in this category of GST and learning research. This list is not intended to be either comprehensive or exhaustive.

1. What technological, pedagogical, and/or content knowledge (and all combinations) is required for teachers to effectively use GST?
   a. Does the use of GST in different content areas require different technological pedagogical content knowledge (TPCK)?
   b. Do different GSTs require different technological pedagogical content knowledge (TPCK)?
2. What are the best practices in providing professional development for GST in education to teachers?
   a. Do these vary by content area, prior experience with GST, grade level, student population, teacher background and experience?
   b. How can PD embedded within curriculum with geospatial technologies be designed to effectively promote the geospatial TPCK of teachers?
3. Are GSTs effective in the context of project-based curriculum or inquiry-based investigations?
4. Are there different PD models and modalities that effectively use GST to support both teacher and student learning?
5. What designs and implementation of instructional sequences using GST will enable students to make connections to larger and more complex problems and/or issues?
6. Are there designs that support teachers' development of students' geospatial thinking and analysis skills, construction of explanations from geospatial data, and ability to support claims with geospatial data (Bodzin, Peffer, and Kulo 2012; MaKinster, Trautmann, and Barnett 2014).

Note: GST = geospatial technologies; PD = professional development ; TPCK = technical pedagogical content knowledge.

Weigand 2003; Shin 2006; Doering and Veletsianos 2007; Milson and Earle 2007; Lee and Bednarz 2009; Perkins *et al.* 2010; Bodzin 2011; Ebenezer, Osman, and Ebenezer 2011; Goldstein and Alibrandi 2013). Many of these studies lack theoretical descriptions of the instructional model and key design principles used in the curriculum design, gaps that limit the reliability and replicability of their conclusions. Larger-scale efficacy or effectiveness studies that examine the impact of GST-integrated curriculum models or design principles on students' content learning or geospatial thinking skills will provide much more useful and implementable knowledge, especially as applied to core disciplinary areas. We also call for studies to investigate different GST interfaces and different uses of data visualizations to understand how to best design GST to promote learners' geospatial thinking and reasoning.

Reform-based curricula, such as those that integrate GST in learning, are viewed by many as an important mechanism for change in education. The curriculum impacts what teachers do, and therefore, what students learn. When teachers implement reform-based curriculum materials, variations with regard to fidelity can occur that may or may not be beneficial to the students' learning (Penuel and Means 2004; Fogleman, McNeill, and Krajcik 2011; Lynch, Pyke, and Grafton 2012). That is, when a teacher adopts a GST-integrated curriculum, he or she has decided that this instructional learning activity is best suited to achieve the desired student learning goals. Such decisions are guided by a teacher's instructional beliefs, intentions, pedagogical implementation skills, and teaching goals (Tarr *et al.* 2008). To promote the geospatial understandings of teachers, curriculum and curriculum supports can be developed to enhance their capacity to effectively use GST. For example, some studies have focused on professional development initiatives to help teachers learn to integrate GST into existing curriculum (e.g., Wilder, Brinkerhoff, and Higgins 2003; Trautmann and MaKinster 2010; Hagevik 2011; MaKinster, Trautmann, and Barnett 2014). Future research studies are needed to understand which types of pedagogical implementation supports may help teachers more effectively implement successful pedagogical approaches to promote student geospatial thinking skills.

To date, we know little about how teachers enact a GST-integrated curriculum (e.g., Kulo and Bodzin 2013). In the future, studies that collect observational data with fidelity of implementation protocols will provide a more comprehensive measure of how teachers adhere to instructional models or important design principles of this type of curriculum. Such information will contribute important insights with regard to the pedagogical strategies that enable geospatial thinking and reasoning skills applied to core disciplinary ideas. Of course, we therefore must learn first what those pedagogical strategies *are* before we can turn to how they are being implemented. Table 5 lists several exemplar questions regarding these topics related to curriculum and student learning with GST.

Research Design and Assessment

In the previous sections, we discussed a research agenda focused on a series of questions. Here we examine *how* these questions might be addressed, that is, the research designs and instruments that will help move the agenda forward. We again assert one of our guiding principles: the deep need for all research in this arena to be conducted following the

Table 5. Research questions pertaining to curriculum design, implementation, and student learning.

Each of these is designed as an example of the type of question that could be posed by a researcher interested in this category of GST and learning research. This list is not intended to be either comprehensive or exhaustive.	
1. How do geospatial knowledge, skills, and practices evolve across learners?	a. How is the development of geospatial knowledge, skills, and practices different across content areas and disciplines? b. How does the development of geospatial knowledge, skills, and practices vary across individuals, settings and time? c. Which geospatial tasks (see Golledge, Marsh, and Battersby 2008) and spatial primitives are developmentally appropriate for curriculum inclusion across different age levels of learners? d. How much use (duration, intensity, format, context, etc.) of GST is enough to provide a measurable learning gain (in the context area of interest)? e. How does the learning context matter? How do learning gains in the areas of geospatial thinking and reasoning skills differ when the use of GST is in the context of a content area versus simply learning the tool? f. How can we optimally design GST interfaces to promote learners' geospatial thinking and reasoning with mobile learning devices? g. What are the hierarchies or linkages between different aspects of spatial thinking? How is spatial thinking developed; do we see progressions in different aspects of spatial thinking across age and grade levels? Do these match with the expectations set out in the standards across STEM disciplines?
2. What are best practices for the design of curriculum and instructional strategies that use GST?	a. What designs effectively promote student content learning? b. What designs effectively promote geospatial thinking and reasoning skills? c. What are the essential geospatial tasks and processes needed to support critical thinking or geospatial thinking and reasoning at a grade level or in a subject area? d. What aspects of a geospatial task or analytical process are most valuable to learners? e. What variations in curriculum enactment occur when teachers implement geospatial technologies-embedded curriculum and how do these variations relate to student's geospatial thinking and reasoning achievement? f. What instructional design features and implementation strategies provide motivational contexts for learning with GST?
3. How do geospatial knowledge, skills, and practices evolve across learners?	a. How is the development of geospatial knowledge, skills, and practices different across content areas and disciplines? b. How does the development of geospatial knowledge, skills, and practices vary across individuals, settings, and time?

Note: GST = geospatial technologies; STEM = science, technology, engineering, and math.

guidelines of sound scientific education research (National Research Council 2002). Research in education related to GST must be evidence-based; link to relevant theory; use appropriate and effective methods; provide a detailed, coherent chain of reasoning to link evidence to theory; describe procedures in sufficient detail to allow replication; be generalizable in a range of settings and populations; and exhibit scholarship through dissemination, peer review, and public scrutiny. These characteristics are both aspirational and essential for the next generation of research around GST and learning to be of higher quality than the last. Of course this is relevant not only for GST educational research, but throughout geography as a whole (Keenan and Fontaine 2012).

Determining the most appropriate and effective methods of research is particularly important in emerging fields of inquiry such as this one, when there are few traditions to fol-low in terms of methodologies. The goals of a study should be matched with the most efficacious research methods. Education research can broadly serve three purposes: (1) foundational, early stage, exploratory research; (2) design and development research; and (3) efficacy, effectiveness, and scale up research (Institute of Education Sciences and National Science Foundation 2013). Each purpose suggests different genres of research, with varying empirical or theoretical justifications, appropriate research designs, and expectations for the types of evidence that are valid.

The purposes of research suggest a trajectory to accumulate a body of evidence. For example, in our context, foundational research will focus on discovering fundamental knowledge about learning with and about GST, "advancing the frontier" of our understandings, and developing new theory. Early stage, exploratory research will further examine these findings to investigate relationships

and build more elaborate theoretical constructs. Design and development research will build on previous work to construct and iteratively test interventions and strategies such as different geospatial curriculum models or teaching methods to contribute to the development of practical theory and tools (Penuel *et al.* 2011). Finally, so-called impact research will examine the question of what works, where, why, and with what supports. Will a geospatial technology curriculum, teaching strategy, or intervention that is successful in suburban Denver be equally effective in inner city Philadelphia? Can the strategy be scaled up and not lose efficacy? Education research is not linear, however, and each type of study can contribute to understandings forwards and backwards by accumulating rich and detailed evidence.

No matter what purpose or research design is selected, the instruments used in the project must be reliable and valid. As described earlier, we lack a range of implicit and explicit instruments and approaches to measuring geospatial learning. This is especially important with regard to the broad GST and learning research agenda that we propose. Previous studies have had to rely on generic spatial thinking assessments derived largely from psychology, such as mental rotation or card folding tests, which may be misaligned and inappropriate for assessment of geospatial thinking. Other research has used GST-specific assessments such as the Spatial Thinking Abilities Test (STAT) (Lee and Bednarz 2012) and Spatial Habits of Mind (SHOM) (Kim and Bednarz 2013), or specific "close" outcome measures (Ruiz-Primo *et al.* 2002) of content knowledge assessments (e.g., Demirci 2008; Huynh 2009; Hagevik 2011). Bodzin (2011) and Huynh and Sharpe (2013) also applied measures of geospatial thinking and reasoning to specific content areas, including geographical knowledge. However, some of these instruments exist only in a prototype, formative stage, and have yet to be statistically validated. Equally important for this agenda, instruments and approaches to assessment that are designed within the context of a single discipline are unlikely to become known to other research stakeholders. Thus we experience an unnecessary and unhelpful duplication of efforts that further undermines the interest in building up a longer history of instrument use and validation.

RECOMMENDATIONS AND CONCLUSIONS

In summary, we suggest a research agenda focused on four interrelated, connected, yet discrete, areas of investigation: the connections between GST and geospatial thinking; how GST are learned in different contexts and by a range of individuals; what curriculum designs and materials facilitate learning; and how to prepare educators to implement GST, that is, professional development. Unless a significant paradigm shift takes place in the field of GST education research, we will continue to plod along with incomplete, fragmented, and inconclusive findings. With each passing decade a new article will plead for more data and evidence,

but real and enduring progress will continue to be difficult. Research in this area is riddled with unknowns, a lack of exemplars, and the inherent challenge of disentangling the technology/pedagogy/content knowledge that this field presents (Doering *et al.* forthcoming). Further, the many bureaucratic and administrative hoops required to access students in classrooms, as well as the lack of familiarity across the relevant content disciplines, have both limited progress.

This can, however, be an ideal time to invigorate, restructure, and refocus the field of research for GST and learning. New tools such as online and mobile GIS platforms have eased the use of technology for students and teachers, while other online resources have also enabled and facilitated collaborative and multidisciplinary research itself, whether it is to help diverse scholars communicate or make it easier to find and access their published research. Establishing new lines of research that are connected with the Common Core State Standards, the Next Generation Science Standards, and the Geography for Life Standards is timely and will leverage the higher public profile of these.

The opportunity is ripe, and certain steps can be realized soon to help reach these ambitious outcomes. In this rich field of GST and learning, multidisciplinary stakeholders lack the type of infrastructure that might otherwise support disciplinary-specific scholars. We recommend that such infrastructure support all stages of the research cycle, from developing and forming partnerships, designing innovative and well-grounded research proposals, identifying funding opportunities and increasing the likelihood of writing successful proposals, conducting informed and robust research with appropriate and effective tools of measurement and assessment, and disseminating results in ways that will reach the relevant audiences and encourage implementation.

Focused efforts to develop and validate geospatial thinking instruments are a high priority task. As noted earlier, instruments must match the types of research being conducted, and with the range required by this agenda we envision a need for several developments, including:

- Tests of basic spatial ability essential in foundational research;
- Content knowledge and geospatial skills assessments linked to specific curriculum interventions and teaching/learning goals to meet the needs of design and development research;
- Content learning measures (including standardized assessments) and authentic problem-solving tasks that involve geospatial thinking and reasoning that can be used in formal and informal contexts by educators as well as researchers for efficacy, effectiveness, and scale-up research endeavors.

Scholars from the range of disciplines interested in GST education will benefit from learning about relevant research that too often remains unfamiliar and inaccessible

behind disciplinary doors. An interactive and open research database would help both junior and senior scholars as they seek to design their research and align it with guidelines, and build systematically on previous studies. Building an informal but robust lexicon of GST educational research terminology, with shared vocabulary (e.g., see Table 1), is a launching step to encourage transdisciplinary conversations. Eventually, a new open-access, peer-reviewed journal may be a desirable solution.

One entity that could support such an outcome is a comprehensive, virtual *Center* for research on geospatial technology in education, to sustain and enable the diverse and sometimes fragile research threads. Having a central *hub* would allow and facilitate the networking and community building that must take place between scholars from the learning sciences, geography, instructional design, STEM disciplines, cognitive sciences, and the many other fields interested in GST questions. As a step in this direction, strategically partnering with the recently-launched National Center for Research in Geography Education (NCRGE) may be one approach for research dissemination, reporting, and data sharing. Presenting a united and coordinated front, with clear and tangible deliverables needed now—in the form of assessment instruments, for example— may aid in obtaining competitive research funding, another critical need for this field.

This research agenda, drafted by a multidisciplinary team of scholars, is indicative of the type of publication that such a Center would be able to support: one that is dynamic and informed by knowledge being regularly accrued by diverse and engaged scholarly communities. Better knowledge around GST and learning is the type of novel scholarship that spans several areas of twenty-first century education and deserves the dedication and commitments that this research agenda will demand. In fact, the more we learn, the more we see GST playing a central and critical role in twenty-first century learning. Yet within educational research, no one discipline "owns" GST, which has meant an absence of steady attention and supportive research infrastructure around it. One need only look around the world today to see that better understanding of the relationships between GST and learning are too important to allow such oversights to continue.

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