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# Towards a holistic framework for delivering quality GIS education within and across disciplines

Paddington Hodza | Margo E. Berendsen | Jeffrey D. Hamerlinck

Wyoming Geographic Information Science Center, University of Wyoming, Laramie, WY, USA

**Correspondence**
Paddington Hodza, Wyoming Geographic Information Science Center, University of Wyoming, Laramie, WY 82071, USA.
Email: phodza@uwyo.edu

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## Abstract

The current GIS education framework has gaps, undervalued elements, and decentralized components that make it difficult to effectively relate, teach, learn, and assess learning key constructs within and across disciplines. Building upon critical synthesis, analysis, and extension of multidisciplinary literature, we develop a student-centered framework that places the 2D learning GIS space within the broader 3D educational space defined by cognitive, affective, and psychomotor domains of learning. The modalities of GIS learning are discussed in the contexts of the "circle of GIS thinking," "triangle of GIS practice," and "triangle of affective GIS." The framework suggests that well-rounded GIS individuals possess hard and soft (non-)geospatial knowledge, skills, and abilities gained through learning by thinking, doing, and feeling. It is coherent, intuitive, extensible, and in sync with modern GIS perspectives and knowledge, and multimodal ways of mastering this subject. We demonstrate how the framework informs design and content considerations for hybrid minds-on, hands-on, and "body-on" classroom assessments that mirror the nature of GIS. We conclude that the framework shows considerable potential to facilitate consistent and persistent delivery of quality GIS education.

  

## 1 | INTRODUCTION

GIS education includes teaching, research, learning, and assessments of student and instructor performance. It extends beyond institutions of higher learning to include K-12 schools, many of which are using digital geospatial tools to support geoinquiry (AP GIS&T Study Group, 2018; Esri Schools Team, 2020). The benefits of widespread GIS education include delivery of citizens with knowledge, skills, and abilities (KSA) valuable in the geospatial technology industry and in creating a preferred future espoused by the United Nations (https://www.un.org/sustainabledevelopment/sustainable-development-goals/) (DOLETA, 2003; National Research Council, 2006; Newcombe, 2006; Shin & Bednarz, 2019; Sinton, Bendarz, Gershmehl, Kolvoord, & Uttal, 2013; Yuan, 2020). We discuss the various KSA later in this article, including spatial thinking, which can be measured to facilitate timely interventions for students in STEM majors (Metoyer, Bednarz, & Bednarz, 2015; National Research Council, 2006; Newcombe, 2010; Uttal, Miller, & Newcombe, 2013).

Looking at the USA, we see that GIS education transcends its traditional home in geography, moving into computer science, engineering, surveying, environment and natural resources, history, agriculture, health, and other departments (Sinton, 2012). The total number, names, prerequisites, and order of delivering GIS courses in different departments vary within and across institutions. These courses generally include separate or combined lecture and lab sessions that may be supported by graduate teaching assistants in different ways and extents. Undergraduate and graduate students are often enrolled in the same classes but held to different expectations regarding classroom participation, quality of assignments, and overall success. GIS courses are not equal within and across departments, and several sections of in-demand classes are usually taught by one or more instructors in the same or over multiple semesters. It is not uncommon to find different instructors employing different syllabi, teaching strategies, learning activities, or classroom tools in similar courses. Similar courses like "Introduction to GIS" are often delivered at multiple division levels, differing in educational rigor and outcomes, both inside and outside institutions.

The picture painted above describes the need for a robust and clear conceptual framework to guide consistent delivery of quality GIS education within and across disciplines and institutions. The various pieces that make up this framework have come from many scholars and evolved over the years (e.g., Burrough, 1986; DiBiase et al., 2006; Goodchild, 1992; Kemp, Goodchild, & Dodson, 1992; Sui, 1995; Unwin, Foote, Tate, & DiBiase, 2012; Wright, Goodchild, & Proctor, 1997). Based on our current knowledge of the continually expanding and advancing field of GIS, plus best practices for teaching, learning, and assessing minds-on and hands-on subjects like this, we argue that the existing framework comprises many *gaps* (e.g., inexplicit appreciation of the significance of the human body as a tool for thinking and learning), *undervalued* and *underemphasized elements* (e.g., soft competencies like emotional intelligence; Mayer & Salovey, 1997), and *decentralized components* (e.g., separate literature on teaching, learning, and learning assessment published by various scholars). This makes it difficult for multidisciplinary stakeholders to effectively relate, teach, learn, or assess mastery of key constructs about GIS, including multiple views, epistemological and ontological assumptions, theories, approaches, tools, and application considerations.

This article critically analyzes, extends, and synthesizes multidisciplinary literature to develop a holistic, comprehensive, and extensible GIS learning framework. This framework places the 2D space of GIS learning (Kemp et al., 1992) within the 3D educational space defined by *cognitive* (Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956), *affective* (Krathwohl, Bloom, & Masia, 1964), and *psychomotor* (Dave, 1970; Harrow, 1972; Simpson, 1972) domains of learning. The underlying objectives, modalities, and outcomes of GIS learning in these spaces are discussed with the aid of clear diagrams and examples. The GIS learning framework is considered valuable to stakeholders like students and instructors, and the former can use it to better connect and appreciate the nature of GIS. The latter can employ the framework, *inter alia*, to guide course design and delivery, and assess how closely the scopes of different courses, curricula, or programs dovetail with what the GIS field entails. In this article, we use the framework to establish and suggest key design and content considerations for a GIS assessment instrument (GAI) test that matches the minds-on and hands-on aspects of GIS. Challenging students to complete hands-on GIS tasks over short periods of time is important to develop and strengthen their skills to cope in fast-paced work environments. This strategy can help meet the growing demand for real-time GIS information, solutions, and decisions in time-critical applications (Gong, Geng, & Chen, 2015; Li, Batty, & Goodchild, 2019). Thus, like other scholars, we propose a hybrid GAI that incorporates software-based exercises completed together with other test sections in single, short sessions.

## 2 | THE NATURE OF GIS

A common starting point for GIS education involves discussing the semantics of S in GIS. Prior to Goodchild's (1992) article, S stood for "systems," which describes GIS as basically technological tools. Burrough and McDonnell (1998, p. 11) formally defined GISystems as "a powerful set of computer-based tools" that bring efficiencies in handling geospatial information. While agreeing with this view, Goodchild posited that S also denoted "science," underlining the significance of GISystems and geospatial information in geoinquiry. This perspective ignited a constructive debate that concluded that the nature of GIS is contextual and describable on a spectrum from tool to science (Figure 1) (Wright et al., 1997). Research and developments in aspects of this spectrum, especially those concerned with meeting societal demands for geospatial information, have recently given rise to another connotation of S, that is "studies" (Longley, Goodchild, Maguire, & Rhind, 2015).

Focusing on GISystems, we find that these tools have many *functions* in real-world applications, including collecting, storing, managing, querying, processing, analyzing, modeling, and displaying geospatial information (Bolstad, 2019; Burrough & McDonnell, 1998; Longley et al., 2015). These functions can be grouped into three categories about geodatabases, geoprocessing (including geospatial data analysis and modeling), and geovisualization (Figure 2) (Esri, 2001). Despite significant advances in each category, GIS remains "flawed" but important, useable, and useful. Many variants—like participatory GIS (PGIS) and qualitative GIS—have emerged over time to resolve one or more issues, emphasize or direct attention to specific features, expand the number and diversity of uses or users, or enhance the overall power of GIS based on high-tech developments (Abdul-Rahman & Pilouk, 2008; Chen, Wang, & Chen, 2013; Cope & Elwood, 2009; Fu & Sun, 2011; Koller et al., 1995; Sinha et al., 2017; Sun & Li, 2016). Like traditional GIS, all these variants are *purpose* driven to build or enhance geospatial understanding, find solutions to geospatial problems, or support geospatial choices (Hodza, 2014; Longley et al., 2015). Achieving each purpose typically involves *geoinquiry*, or posing and addressing questions about one or more aspects of geospatial phenomena, including: (a) locations; (b) conditions or qualities; (c) patterns, relationships, or associations; (d) behavior over time; and (e) possible or future scenarios (Figure 2) (Rhind, 1989).

## 3 | GIS BOK, COURSE OBJECTIVES, AND COURSE OUTCOMES

The views on GIS discussed above influence what is included in the body of knowledge (BoK) on GIS. This BoK is continually updated based on new insights and progress in GISystems, GIScience, and GIStudies (Figure 3). Together with the needs of the geospatial industry and society, the GIS BoK offers a strong ground for building

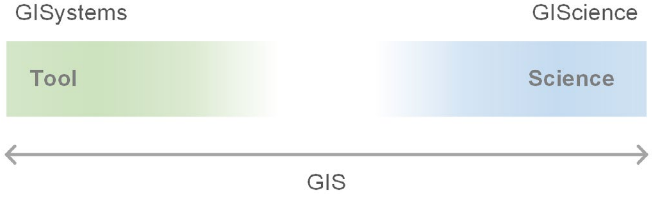


**FIGURE 1** The spectrum of GIS ranges from tool to science

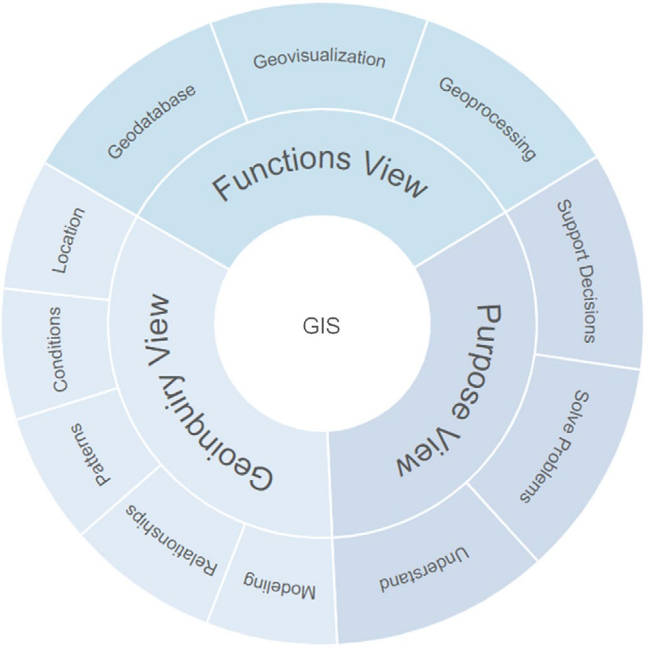


**FIGURE 2** As tools, GIS have many *functions* valuable in achieving one or more *purposes* through *geoinquiry*

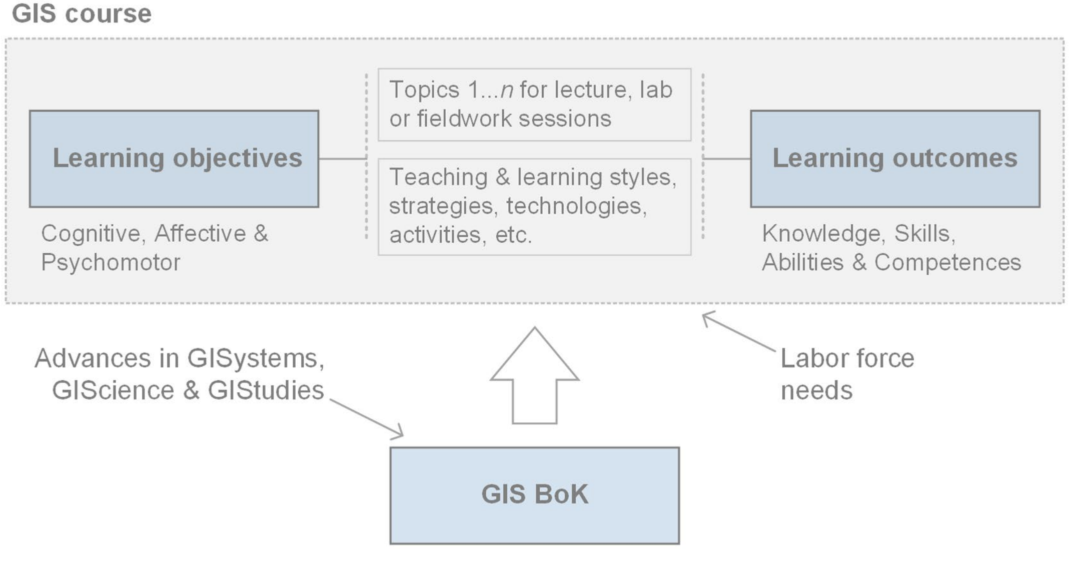


**FIGURE 3** GIS courses are informed by the GIS BoK and prioritized needs of the geospatial industry and society. Closing the gap between GIS learning objectives and outcomes involves multiple teaching and learning activities, tools, and methodologies plus cognitive, affective, and psychomotor competencies

and maintaining GIS curricula that are relevant and cutting-edge. The connections between the GIS BoK, course objectives, course outcomes, and course content are discussed below in the broader context of GIS education.

### 3.1 | GIS BoK

The GIS BoK comes in many forms, with elements like GIS principles, practices, and implications on society (DiBiase et al., 2007; Sinton & Kensky, 2020; Wilson, 2014). The elements were initially *distributed* and available in course materials like textbooks, journal articles, software workbooks, and other (un)published multimedia (Johnson, 2019; Kemp, 2012). Although these resources continue to inform GIS education, many instructors are increasingly drawing on *self-contained* forms of the GIS BoK (e.g., https://gistbok.ucgis.org/), developed and maintained through concerted efforts. This observation was confirmed by a recent survey in which most respondents ($n$ = 109, 61% = faculty) ranked teaching as their most important use of the current GIS&T BoK, ahead of professional development, research, professional practice, scholarship, and "other" uses in that order (Moore, 2019). This is possibly due to the fact that this BoK is a comprehensive one-stop shop for up-to-date, peer-reviewed knowledge that is readily accessible both openly and online.

While self-contained GIS BoKs like GIS&T BoK, GEOINT Essential BoK, and GI-N2K are all instrumental in designing course syllabi, preparing lectures, lab and fieldwork content, as well as developing learning assessment tools, there are no specific guidelines on: (a) how to pick and choose topics; (b) how selected topics should be sequenced; or (c) how rigorously each topic should be taught at lower, intermediate, or upper division levels. The exception is probably the NCGIA core curriculum, which nominally presents topics in order of increasing complexity from "What is GIS?" to "Storage of complex objects," "GIS application areas," and ending with an important outlook on the future of GIS (Goodchild & Kemp, 1990).

### 3.2 | GIS learning objectives

Although each topic entry in the GIS&T BoK includes concise learning objectives and instructional assessment questions that can be adapted for instructional purposes, an important step towards identifying relevant content for adoption involves establishing "SMART" (i.e., specific, measurable, attainable, realistic, and time-bound) course objectives. SMART course objectives are also a prerequisite for formulating appropriate learning outcomes and assessments (Figure 3). They are exemplified by Bloom et al.'s (1956) revised taxonomy (Anderson et al., 2001) used by many GIS instructors (e.g., Prager & Plewe, 2009) to articulate what students will learn in the *cognitive* domain, that is, to *remember*, *understand*, *apply*, *analyze*, *evaluate*, or *create* various course content. But GIS education also extends into *affective* and *psychomotor* domains, which must also be reflected in course objectives to applicable extents (DeMers, 2009; Liu, Bui, Chang, & Lossman, 2010).

There is little information about the extent to which self-contained GIS BoKs cover the scopes of the three domains of learning. Most of it is about the cognitive area and comes from DeMers (2009), who uncovered that virtually all knowledge areas of the first GIS&T BoK (DiBiase et al., 2006) addressed *comprehension* and *application* objectives (Bloom et al., 1956) instead of complex problem-solving that was the intended focus. Indeed, it is in assisting users to execute more complex objectives like multivariate geospatial *analysis*, *evaluating* geospatial solutions, or *creating* new geospatial tools that the greatest strength of GIS lies (Sinton & Bednarz, 2007). Liu et al. (2010) demonstrated this strength in problem-based learning, where GIS users were quick to apply geospatial knowledge, and became more analytical and evaluatory in their approaches than individuals who did not use the technology and only completed simple geospatial cognition tasks.

### 3.3 | GIS learning outcomes

GIS learning generates many outcomes that can be expressed in soft (e.g., work ethic and oral communication) and hard (e.g., map production) KSA terms (Wikle & Fagin, 2015). Competencies encompass these KSA and are placed in models that differ in terms of driving forces, scopes, target audiences, uses, granularity, and other characteristics (DiBiase, 2018; Johnson, 2019). A rigorous one-to-one mapping and granular analysis of the differences and similarities between various models of GIS learning outcomes is important but challenging due to wide-ranging terms, meanings, and classifications assigned to different competencies. Here, we highlight that:

- **Competence models are not necessarily a one-size-fits-all contexts type of tool**. For example, Marble's (1998) model targets GIS student education, while DOLETA's (2018) supports professional development. The former recognizes that GIS are intrinsically digital and geospatial, and thus treats "basic spatial and computer understanding" as cornerstone competencies of undergraduate GIS education. Stacked on this foundation are five competencies students are also expected to develop, that is: (1) routine use of basic GIS technology; (2) higher-level modeling applications; (3) GIS application design and development; (4) GIS system design; and (5) GIS research and software development. Prager and Plewe (2009) linked Marble's model to the cognitive taxonomy (Anderson et al., 2001), creating a tool for evaluating the learning outcomes of two undergraduate "Introduction to GIS" courses. They found that both courses emphasized developing minds-on/hands-on competencies consistent with the first three levels of Marble's model. This indicated the need to update the courses with content and activities that addressed higher model levels.
- **Competence models and learning GIS outcomes are not solely about geospatial KSA**. They include non-geospatial KSA (e.g., intrinsic motivation) that come in handy when working independently or collectively with others on GIS projects (DiBiase, 2018). This implies that well-rounded GIS individuals possess both geospatial and non-geospatial KSA, and the latter are explicitly captured under personal/interpersonal competencies in the Geospatial Technology Competence Model (GTCM) (DOLETA, 2018) and Gaudet, Annulis, and Carr (2003) model.
- **Competencies are not equal within and across models**. For example, Gaudet et al.'s (2003) model comprises 39 competencies but only 15 are considered core. Interestingly, five of the core competencies fall under interpersonal and four each come from technical and business categories. DiBiase's (2018) model groups technical competencies into "positioning and data acquisition," "analysis and modeling," and "software and application development," and considers the second set paramount for GIS professionals. The relative importance of competencies is, however, not cast in stone, since innovations, developments, and trends in the GIS&T field plus dynamic workforce needs of the geospatial industry all prompt regular reviews and updates to competence models (DiBiase et al., 2006).

## 4 | 2D AND 3D LEARNING GIS SPACES

Drawing insights from Kemp et al. (1992, p. 189), we argue that many (non-)geospatial competencies are cultivated during two complementary processes involving "learning about GIS" (LAG) and "learning to work with GIS" (LWG). One study supporting this argument found that students engaged in these processes developed stronger science, social studies, reading, and spatial thinking skills than those who were not (Goldstein & Alibrandi, 2013). The two processes delineate a 2D learning GIS space (Figure 4), where emphasis on either one can be light or heavy, depending on factors like course type, objectives, learning outcomes, topic (e.g., geospatial analysis vs. GIS ethics), and access to GIS technology. Although LAG focuses on GISystems, this process can be completed *with* or *without* GIS technology (Kemp et al., 1992). The latter is exemplified by point A, where GIS theory is favored over practice. It can involve "paper GIS" that are "important for teaching conceptual issues of GIS" (Rust & Sweidan, 2008) but inconsistent with modern perspectives, challenging and inefficient when handling large or complex datasets.

Geoinquiry represents one approach for achieving LWG at point C. The outcomes at this position include practical competencies developed through reproducing or replicating previous GIStudies (Kedron, Frazier, Trgovac, Nelson, & Fotheringham, 2021) or by exploiting GIS in novel geoinquiry assignments. These competencies can

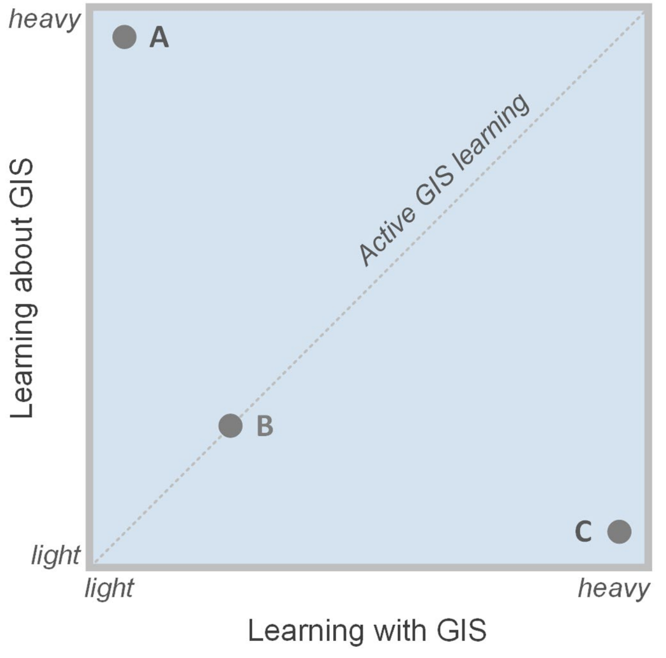


**FIGURE 4** The learning GIS space is defined in LAG and LWG dimensions that receive equal emphasis in certain forms of active learning

also be acquired along the diagonal line (e.g., point B) where LAG and LWG have equal emphasis and many GIS courses or modules are increasingly delivered. Associated with this line are active learning approaches that are place, problem, or inquiry-based, and known to demand heightened student motivation, engagement, organization, and flexibility (Favier & Van der Schee, 2012; Liu et al., 2010). While operating on this line, Srivastava and Tait (2012) had students assume leadership and responsibility for creating custom analog and GIS maps through several incremental weekly activities. The result was deep student fluency in GIS technology, map-making, and mapping concepts.

Figure 5 illustrates that the 2D learning GIS space exists within the broader 3D educational space defined by cognitive, affective, and psychomotor learning domains. Instances of the interface between these spaces can be discussed with reference to positions X, Y, and Z. At point X, learning GIS involves complex cognitive skills and tasks (e.g., geospatial analysis and problem-solving) but simple psychomotor (e.g., keyboard data entry) and affective skills (e.g., indifference to available GIS software). Complex psychomotor tasks (e.g., flying a drone and collecting geospatial data through hand gestures) and simple affective and cognitive tasks are the norm at position Y. Many upper-division and graduate-level courses take place at Z, where topics are typically in-depth and cognitive, psychomotor, and affective tasks require overall advanced skills. Although the tasks completed at this position—such as *evaluating* and *creating* (from Bloom et al.'s, 1956 revised cognitive taxonomy), *receiving* and *responding* (from Krathwohl et al.'s, 1964 affective taxonomy), and *skilled movements* and *non-discursive communication* (from Harrow's, 1972 psychomotor taxonomy)—are considered complex in their respective taxonomies, GIS can aid their execution in non-demanding mental and physical ways. This is possible with naive GISystems (Egenhofer & Mark, 1995; Hamerlinck, 2015) that afford a more intuitive user experience (UX).

Each unique side of Figure 5 accentuates one or more constructs that have received or are attracting growing attention in the geospatial field. In essence, the *cognitive–affective* side describes the plane of emotional intelligence (see Section 5.3), a soft competence that can yield benefits when resolving contentious issues with GIS, for example. Young and Gilmore (2013) applied this competency to create a video-enabled GIS map capable of

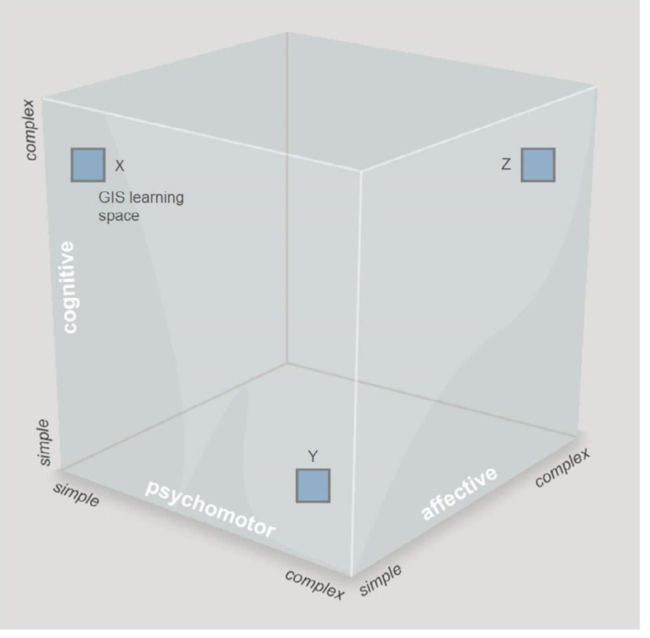


**FIGURE 5** Learning about/with GIS takes place within a 3D space defined by cognitive, psychomotor, and affective learning domains

appealing to the emotions of change agents external to indigenous communities. The *cognitive–psychomotor* interface highlights embodied cognition, which treats the body as a thinking tool much like the mind (Wilson & Golonka, 2013). Embodied cognition is possible in immersive geovirtual or GIS environments where multiple sensory modalities, non-linguistic body movements, and multimodal learning can be supported (Hodza, 2009; Knight & Tlauka, 2018). Richards-Rissetto et al. (2012), for example, found that using bodily kinesthetics to explore a geovirtual environment helped "remove" the technology interface providing participants with a lifelike UX. The *affective–psychomotor* plane draws attention to the affective motor system, which benefits from technology that responds to voice commands or gestures like those based on our emotions (Yamauchi & Xiao, 2018). Gesturing is a natural mode of interaction that can be enabled by motion-sensing devices like Microsoft Kinect used by Richards-Rissetto et al. (2012) to facilitate retrieval of virtual feature attributes.

## 5 | MODALITIES OF LEARNING GIS IN 3D EDUCATIONAL SPACE

We adopt intuitive terms used by other scholars to describe what the three domains of learning basically entail, such that learning GIS in the 3D educational space is synonymous with learning by *thinking* (i.e., cognitive), *doing* (i.e., psychomotor), and *feeling* (i.e., affective). The underlying concepts, modalities, and key outcomes of these processes are discussed below.

### 5.1 | Modalities of learning GIS by thinking

Anderson et al. (2001) suggest that learning GIS involves six levels of thinking activities identified in Section 3.2. To complete these levels, students think with their minds and bodies (i.e., *embodied* cognition; Wilson &

Golonka, 2013), while: (a) working independently or as part of a team (i.e., *distributed* cognition) (Hutchins, 1995; Wright, Fields, & Harrison, 2000); (b) interacting with various things in the environment (i.e., *enactive* cognition; Malinin, 2016); or (c) drawing on their worldviews, the opinions of others, or other factors (i.e., *situated* cognition; Malinin, 2016). Examples of these modalities include "thinking with and through the hands" (i.e., embodied cognition) to evaluate or solve spatial problems (Antle, 2013, p. 941) and mental mapping exercises that separately engage warring groups to create a complete picture, understand and analyze land disputes (i.e., situated cognition; Weiner & Harris, 2003).

While operating at different thinking levels, students can leverage many subtypes of the above forms of cognition closely related to GIS. Looking at the nature and linkages between these subtypes is important to solidify understanding of cognitive learning. Baker et al. (2015) identify *geospatial thinking*, which is enabled and enables effective use of geospatial technologies in general. However, how we think through GIS (i.e., *GIS thinking*) is not necessarily the same as how we think by means of GPS, UAS, geovisualization, or other geospatial technologies. GIS thinking is about acquiring (and applying) geospatial knowledge with the aid of GIS. Drawing inference from the National Research Council (2006), we conclude that GIS thinking encourages, facilitates, and supports *spatial thinking*. Competency in spatial thinking includes knowledge of spatiotemporal concepts (e.g., topology, scale, and historical time), skills to exploit tools of representation (e.g., visual and computational), and abilities to reason (e.g., formulate hypothesis) about real-world problems (Goodchild & Janelle, 2010; Metoyer & Bednarz, 2017; National Research Council, 2006). This competency is foundational to *geographic thinking*, which is useful for investigating the essence of spatiotemporal patterns and relationships between geospatial phenomena as well as developing solutions for geospatial problems (Canadian Geographic Education, 2019; Metoyer & Bednarz, 2017).

The connections between various thinking modalities triggered and achieved with GIS are captured by the "circle of GIS thinking" (Figure 6). Each modality in this diagram can be engaged with in critical, creative, and collaborative ways. Critical means that we go beyond mere interaction with geospatial tools and become "reflective, skeptical, or analytic ... of assumptions, techniques, and data ... to meet the rigorous standards of good scholarship" (Goodchild & Janelle, 2010, p. 9). This includes raising questions about geospatial data integration, analysis, and modeling approaches that are computational and visual in nature and commonly used to achieve GIS thinking.

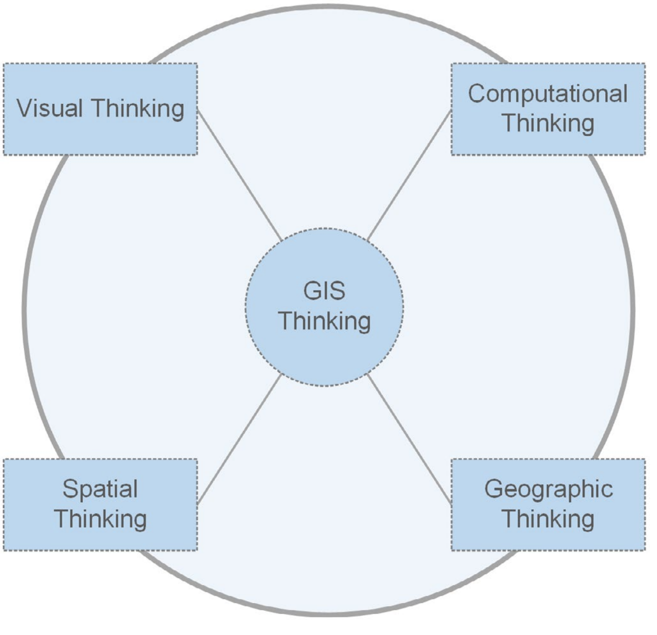


**FIGURE 6** Common thinking modalities used with GIS motivate, augment, support, or facilitate each other

It follows that GIS thinking involves *computational thinking* (Wing, 2006, 2008) and *visual thinking* activities. The latter exploits the geovisualization component of GIS, which revolves around visual representations like 2D/3D web maps, interactive graphs, and animations (MacEachren, 1994; MacEachren et al., 2004). These and other visual representations are crucial in geoinquiry where they are used to *visually* present, synthesize, confirm, analyze, and explore geospatial data to expose, understand, and explain the nature (e.g., topological relations) of geospatial phenomena (DiBiase, 1990; MacEachren et al., 2004). They are also effective classroom tools, especially for students who learn in visual ways (Xiang & Liu, 2018). These students exhibited better spatial thinking skills than those who learn kinesthetically after exposure to a largely visual web GIS, indicating that visual thinking basically aids spatial thinking (Xiang & Liu, 2018).

Like other modalities, visual and computational thinking complement each in thinking, learning, and reasoning about/with GIS. Examples of GIS activities that employ the latter include semantic geodatabase design, workflow development using Esri ModelBuilder (Hall & Post, 2009), and geospatial analysis and modeling. While users can enhance their understanding of geospatial phenomena and problems through computational thinking, this modality is primarily meant to transform these "issues" into ways GIS can computationally handle. Computational thinking is generally completed in four steps involving decomposition, pattern recognition, abstraction, and planning algorithm-based workflows (BBC, 2020). The guiding principle is that complex problems are best solved by initially reframing them into two or more simple sub-problems. Each sub-problem (e.g., how to represent terrain elevation) is then examined and, where possible, matched with existing solutions (e.g., digital elevation model and relief shading) through pattern recognition. Next, elements (e.g., edge artifacts) regarded as critical to solve a sub-problem are identified and generalized through abstraction before incorporation in algorithmic solutions.

## 5.2 | Modalities of learning GIS by doing

There are three psychomotor taxonomies (Dave, 1970; Harrow, 1972; Simpson, 1972) that can be used to inform learning GIS by doing. Each taxonomy comprises five to seven hierarchies of kinesthetic competencies relevant

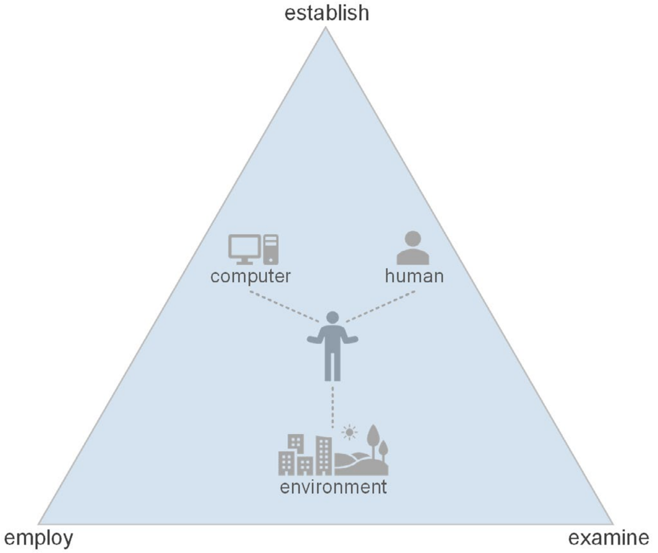


**FIGURE 7** Learning GIS by doing GIS involves establishing, employing, and examining GIS. These activities involve reciprocal interactions between GIS, people, and the environment, and exploit our sensory modalities and body movements

for doing GIS in different ways and degrees. Doing GIS broadly involves *establishing* usable GIS, *employing* GIS to transition to a desired state, and *examining* issues associated with building, applying, and maintaining GIS (Wright et al., 1997). Interconnecting these activities creates the "triangle of GIS practice," where people are a significant and central part (Figure 7). This space is action-oriented and indicates that learning GIS by doing involves three types of user-centered interactions: human–computer interaction (HCI), human–human interaction (HHI), and human–environment interaction (HEI). Human-independent interactions such as computer–computer interaction (CCI) that take place in this space are important but fall outside the scope of our study.

The HCI dimension underscores the need and benefits of hands-on interactivity with GIS (i.e., the "computer") (Haklay, 2010; Nyerges, Mark, Laurini, & Egenhofer, 1995) while learning in the 3D educational space. This interactivity provides the best modality for students to deepen their knowledge of geospatial concepts (e.g., scale-dependent display); further understand how GIS work and build practical GIS skills; complete wide-ranging geospatial tasks (Roth & MacEachren, 2016; Tobon, 2005; Vahedi, Kuhn, & Ballatore, 2016); and evaluate GIS based on first-hand experience. It allows students to work with GIS technology to build, query, and manage geodatabases; generate, geovisualize, and share geospatial information; make data-driven decisions; and plan or implement geospatial solutions (Albrecht, 1998; Haklay, 2010; Nyerges et al., 1995). The GIS technology and methodology can generate different reactions from different people (Berendsen, Hamerlinck, & Webster, 2018; Haklay, 2010), which can be documented, analyzed, and used by students to recommend improvements or create new and more advanced versions.

Paraphrasing the words of English poet John Donne, we hold that the HHI dimension implies that "no human being is an island" in doing GIS. This means that effective conversations are crucial in learning and doing GIS, such as when seeking technical support and creating geospatial solutions that affect others, respectively. GIS conversations can be fostered through group assignments where students can exchange ideas in person, via video conferencing, or through geovisualization tools, and learn from each other to be team players or leaders. Groups evoke distributed cognition that is capable of improving individual understanding of geospatial concepts, techniques, problems, and solutions (Hodza, 2009). This finding was echoed by students in groupwork who "felt that interacting with peers … and overcoming challenges in an open-ended research environment provided better ways to improve their GIS skills and abilities than traditional labs and lectures" (Bowlick, Bednarz, & Goldberg, 2016, p. 197). The different extents of student participation observed in this study suggest that groupwork presents opportunities to learn to navigate situations involving different personalities, skills, views, and commitment levels among members without compromising overall group productivity.

The HEI factor implies that it is not sufficient to interact with GIS worlds as we gain a lot from participating in the real world. An example of the latter involves visiting a solid-waste landfill to gain first-hand insight, collect data, or prescribe solutions about environmental concerns like visual blight, foul odor, or land pollution. Put differently, the field environment allows students to *see* and appreciate natural and built environments, including geospatial processes in action; *smell* various things; *hear* sounds of nature; *move* around to experience different terrains; *touch* and feel different things; *taste* and appreciate many foods; or *examine* human impacts on the environment. Some of these sensorimotor experiences can be realized in high-fidelity immersive geovirtual or GIS environments, albeit to varying extents (Hodza, 2009). This was apparent in Klippel et al.'s (2019) study, where students who went on a virtual geology field trip found the experience fun, enjoyable, and engaging, and got better grades for the field exercise than those who went on a real trip, illustrating that geovirtual environments can facilitate deep knowledge development.

## 5.3 | Modalities of learning GIS by feeling

Learning GIS by feeling places affects front-and-center in GIS education. Affects encompass our emotions and feelings (Kwan, 2007), which manifest as bodily (e.g., facial expressions) and mental (e.g., happiness) states,

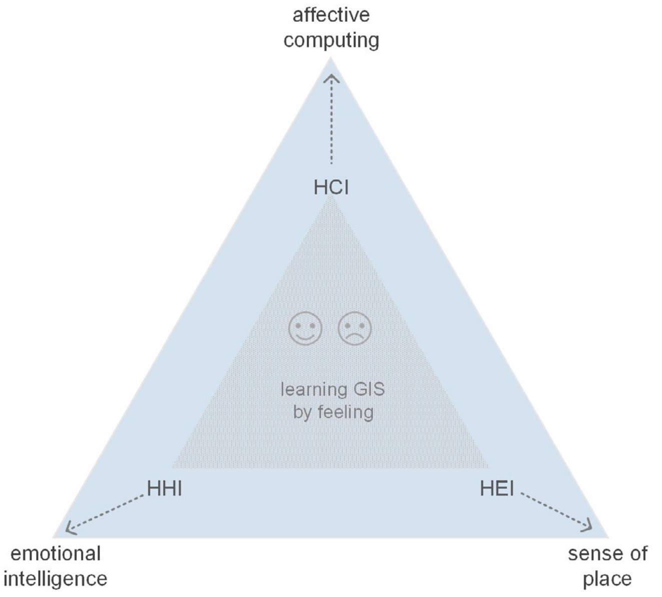


**FIGURE 8** Learning GIS by feeling can be understood in the context of the *triangle of affective GIS*, which identifies emotional intelligence, affective computing, and sense of place competencies as major outcomes

respectively (Schmidt, 2017). Affects require *emotional intelligence* to perceive, organize, make sense of, and act on in appropriate and effective ways (Goleman, 1995; Krathwohl et al., 1964; Mayer, Caruso, & Salovey, 2016). They motivate us to discuss the modalities of learning GIS by feeling from three positions that recognize the centrality of people in doing GIS: HHI, HCI, and HEI (Figure 8).

With regard to HHI, we obtain ideas from Hall and Hall (2012) and contend that emotional intelligence is the underlying framework and intended outcome of learning GIS by feeling. This competency is one of 10 most critical for individuals and businesses to compete and succeed in the fourth industrial revolution (WEF, 2018). It can be developed though role-play exercises that give students opportunities to learn to be empathetic and considerate of others' affects (Hall & Hall, 2012). An example of these exercises is a pretend community GIS project in which students are assigned different roles (e.g., planners, developers, community members, and focus group facilitators) to deliberate on future developments and related societal and environmental impacts. Students could also be engaged in: (a) preparing and asking interview questions that prompt affective responses about local geospatial problems; (b) conducting affective analyses of stakeholder perceptions of controversial issues like wind power and climate change; or (c) creating, applying, and assessing the effectiveness of emotive GIS products (e.g., animations of mining impacts on landscapes) to achieve desired affects and project outcomes.

As viewed from the perspective of HCI, a key outcome of learning GIS by feeling is competency in *affective computing*. Individuals with this competency can employ qualified digital technology to detect, process, and motivate or respond to wide-ranging affects (Hudlicka, 2003; Picard, 2003; Tao & Tan, 2005). This implies that GIS are capable of feeling us, and we can also feel with them. The former is possible through various artificial intelligence devices and methods, but is beyond our scope of study. The latter involves handling emotional, sentimental, and attitudinal data, and generating geospatial knowledge, decisions, solutions, or actions that are sensitive to stakeholders' affects (Kang et al., 2019; Kwan, 2007; Young & Gilmore, 2013). It is exemplified by Lopez and Lukinbeal's (2010) work, which shows that affective computing skills can be acquired through GIS mental mapping that empowered stakeholders to share their feelings about neighborhood crime. Additionally, students could complete assignments that involve creating geospatial stories embedding oral histories about affective experiences of local people during specific time periods or events (Carroll, 2017). Without access to primary sources, students could also learn to create GIS maps incorporating affective data harvested from secondary sources like social media (Huang et al., 2010). Furthermore, they could be taught to analyze and draw affective conclusions (e.g., distrust of the state) from the words, voices, and postures of individuals in geospatial video narratives (Curtis et al., 2015; Young & Gilmore, 2013).

Looking at learning GIS by feeling through the HEI lens reveals *sense of place* as a major outcome. Competency in building this sense is useful for appreciating and managing one's positionality, posing the right questions, and arriving at relevant conclusions in place-based GIS investigations. Wilkie and Roberson (2011, p. 138) describe sense of place as "feelings and experiences of our world's great range of places." They cite Lopez (1998, pp. 412–143) who concisely explains how this understanding is developed by saying: "It is through the power of observation, the gifts of eye and ear, of tongue and nose and finger, that a place first rises up in our mind; afterward it is memory that carries the place, that allows it to grow in depth and complexity." Thus, learning activities that inspire and support constructing a sense of place include field trips focused on describing locations from first-hand experience based on the dimensions of this concept (Adams, Greenwood, Thomashow, & Russ, 2016). To varying degrees, sense of place can also be gained by interviewing others about their experiences in different locations (Adams et al., 2016). What is felt, experienced, or shared about a given location can vary between individuals in terms of, for example, levels of affective connection (i.e., place attachment) and social significance, or value given to that site (i.e., place meaning) (Jorgensen & Stedman, 2001; Masterson et al., 2017; Raymond, Kyttä, & Stedman, 2017). These differences provide a chance for students to learn about how our sensory and motor skills, plus other factors (e.g., individual interests), influence sense of place (Adams et al., 2016; Huang et al., 2010).

## 6 | GIS ASSESSMENT INSTRUMENT DESIGN AND CONTENT CONSIDERATIONS

Figure 9 pieces together the main elements of the GIS learning framework. We leverage this framework to articulate the possible structure and content of a sound GIS assessment instrument (GAI) that can be used summatively in introductory GIS courses. A sound GAI is grounded in course content, readable, authentic, challenging, and reliable in measuring students' KSA in GIS (e.g., Baker et al., 2015; Downs, 2011; Huynh & Sharpe, 2013; Schulze, Kanwischer, & Reudenbach, 2013). It is also minds-on, hands-on, and "body-on" like the GIS subject (AP GIS&T

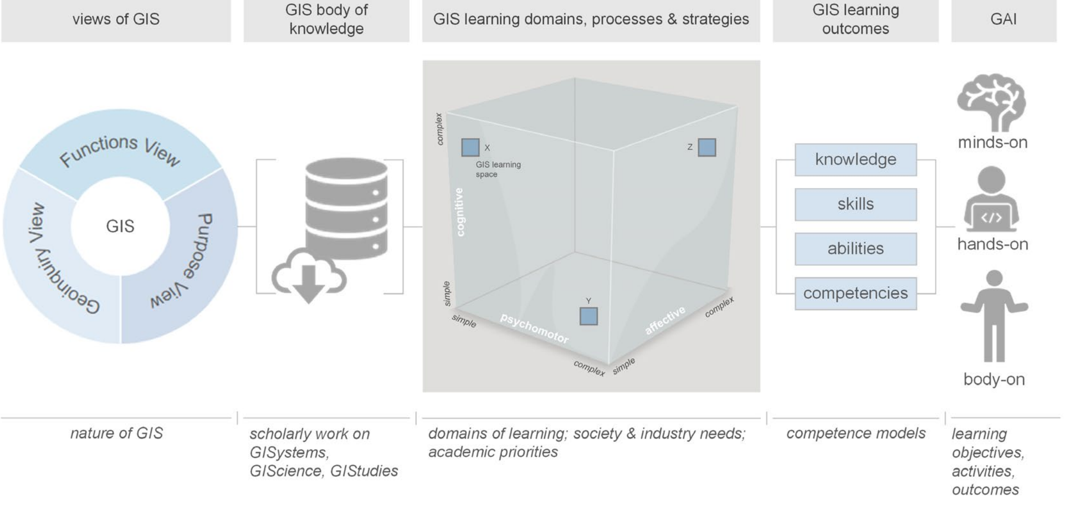


**FIGURE 9** A diagrammatic summary of the main building blocks of the GIS learning framework. The text below each block identifies the drivers, concepts, principles, etc. that shape that aspect

| | Course objective | Course topic | GIS&T BoK knowledge area | Learning outcome | GIS purpose view | GIS functions view | Geoinquiry view | Thinking modality |
|---|---|---|---|---|---|---|---|---|
| MC1 | | | | | | | | |
| MC2 | | | | | | | | |
| MC3 | | | | | | | | |
| FR1 | | | | | | | | |
| FR2 | | | | | | | | |
| FR3 | | | | | | | | |
| HE1 | | | | | | | | |
| HE2 | | | | | | | | |
| HE3 | | | | | | | | |

**FIGURE 10** A GAI crosswalk table can support designing and developing sound summative tests or exams. Table columns can be as many as desired. MC1, FR1, and HE1, respectively, stand for the first questions of multiple choice, free response, and hands-on exercises

Study Group, 2017; Mathews & Wikle, 2019). These aspects can be addressed in a multipart GAI made up of: (a) a traditional classroom test comprising multiple choice (MC) and free response (FR) questions; and (b) a generously timed (i.e., days or weeks-long) applied GIS project that can be done “at home” (AP GIS&T Study Group, 2017).

Although standalone GAI parts can be administered at different times under different rules, guidelines, or conditions, rising demand for real-time GIS (Gong et al., 2015; Li et al., 2019) motivates us to propose an assessment tool completable in one sitting lasting a few hours (i.e., <3). This GAI is also hybrid but consists of three sections on: (a) MC questions that require applying simple cognitive and psychomotor (e.g., handwriting or keyboard typing) skills; (b) FR questions that evoke affective and complex cognitive skills while one is analyzing and evaluating information; and (c) GIS software exercises that engage cognitive, psychomotor, and affective skills. These sections need not be equal but must all be consistent with applicable 3D educational space learning objectives, the focus of teaching about/with GIS, and learning GIS by thinking, doing, or feeling activities. Their individual weights depend on many factors, such as degree of alignment with overall course objectives.

A good starting point for preparing GAI content is to identify relevant aspects of the GIS learning framework in a crosswalk table (Figure 10). This table is not set in stone, and should be modified if it reveals gaps, unintended biases, or misalignments between GIS learning goals, activities, and outcomes. Its granularity can be coarse or fine-grained, such as populating different cells with simple “Yes/No” answers or indicating that “valuing” is the affective learning objective addressed by a given FR question or hands-on exercise. Anecdotal evidence indicates that many instructors use formal checklists like this crosswalk table to make sure that tests cover desired course content.

The software-based section of the GAI can be challenging to design for and dry run to ensure that it is do-able within a planned timeframe without issues. Drawing on Figure 2, each hands-on exercise must achieve one or more GIS purposes, and require students to apply geodatabase, geoprocessing, and geovisualization concepts, tools, and methods while completing geoinquiry tasks concerning future trajectories of geospatial phenomena, for example. While access to a wide variety of geospatial apps for field data collection, desktop data analytics, and online data geovisualization, for example, has encouraged many instructors to expose students to multiple GIS software in a single course, allowing students to complete hands-on GAI exercises using personally preferred software can be problematic. This is because average completion times and overall test durations may vary with software, and impact fair administration and proctoring. A possible solution for courses that require mastery of *several* software might involve asking students to use specific software to complete given exercises (e.g., QGIS for HE1, ArcGIS for HE2, Idrisi for HE3, or ArcGIS Online for HE4). The exercises should not merely prompt students to recall menu items to point and click (i.e., simple cognitive tasks), but also require them to critically examine the end-to-end GIS problem-solving process (i.e., involve complex cognitive tasks) (i.e., Baker et al., 2015; Goodchild & Janelle, 2010; West, 2012).

As diverse majors are often mingled in the same GIS courses, it is important to identify universally appealing or affectively neutral geospatial phenomena or problems to address in GAI tests. Since this is difficult to achieve, educators could design GAI tests that allow students to address, say, only three out of a choice of six exercises on multiple problem themes (e.g., land cover change detection for HE1, crime hotspot analysis for HE2, and analysis of infectious disease spread for HE3). These exercises must be similar in GIS data types (i.e., vector, raster, and tabular), technical and non-technical concepts (e.g., reproject, buffer, and overlay), complexity and challenge, completion times, and other key factors. Including questions on multimedia content (e.g., discuss affects in video narratives) and requiring answers that are supported by annotated diagrams can help ensure the GAI mirrors students' visual, auditory, and kinesthetic learning styles.

## 7 | DISCUSSION

While appreciating the linkages between teaching, research, learning, and other educational activities, our study focused on developing a student-centered framework that underpins deep GIS learning and designing effective assessment tools. This framework critically integrates and presents multidisciplinary constructs in a narrative driven by intuitive figures for different stakeholders to easily comprehend, adopt, extend, or apply. It incorporates contemporary GIS perspectives and knowledge, and encourages a multimodal learning approach that motivates formulating SMART learning objectives covering cognitive, affective, and psychomotor domains. The various framework figures have instructional value and can be used by both educators and learners to better connect and comprehend geospatial and GIS education concepts.

By relating GIS learning outcomes to various geospatial competence models, the framework paves the way for competence-based GIS education alluded to by Sinton and Kensky (2020). The framework underscores that both geospatial and non-geospatial KSA are essential for GIS individuals to thrive and flourish in the geospatial industry and society in general. By appreciating the value and advocating the development of both hard and soft competencies which may be engaged to varying degrees in individual and group projects, the framework helps neutralize the perceived masculinist biases of GIS epistemologies (Le Noc, 2019). Indeed, based on the triangle of affective GIS, triangle of GIS practice, and circle of GIS thinking, as well as competence models like Gaudet et al.'s (2003) and the GTCM, both hard and soft competencies are relevant to the geospatial field and can be developed while learning GIS by thinking, doing, and feeling. This means that it may not be necessary to take non-geospatial or general education courses to develop these KSA.

Many scholars, like Sui (1995), Clark, Monk, and Yool (2007), and Mathews and Wikle (2019), have looked at different instructional styles, strategies, and approaches for imparting GIS KSA to students. Recognizing that what works in one course, discipline, or institution may not necessarily work elsewhere due to student diversity, differential access to resources, and other factors, Sinton and Kensky (2020) cite DiBiase (2018) and note that "[a] one-size-fits-all instructional model in GIS is not only futile but also outdated and unhelpful." That said, there are two instructional strategies for achieving LAG and LWG processes put forward by Sui (1995, p. 581); that is, "teaching about GIS" (TAG) and "teaching with GIS" (TWG), respectively. The effectiveness of each strategy can vary by instructor and by education domain. This was revealed by Wang and Chen (2013), who surveyed 911 GIS instructors and found that most of them felt more confident operating in the cognitive than the psychomotor or affective domain, largely due to perceived UX issues with available GIS software.

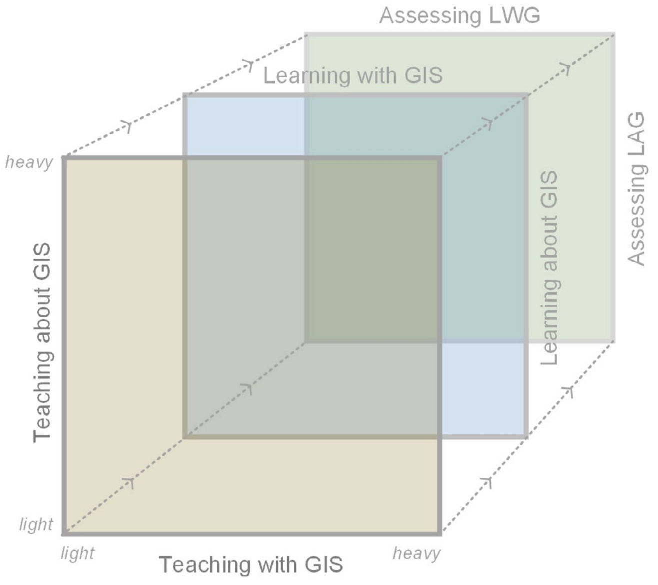


**FIGURE 11** Teaching promotes learning, which in turn influences the scope of what is assessed in GIS education

The upshot here is that effective GIS education requires establishing strong connections and good alignment between teaching, learning, and assessing GIS learning spaces (Figure 11). Instructors are free to operate from any location within the teaching GIS space as long as they meet the learning needs of diverse students, predefined course objectives, and program expectations. Developing in-depth GIS learning experience thus depends on resources, activities, methods, settings, and other factors spread across teaching, learning, and assessing GIS learning spaces. It involves interacting with geospatial data, software and hardware, networks, and others (e.g., peer learners, instructors, and local community members) in cognitive, affective, and psychomotor learning domains while applying appropriate geospatial principles, concepts, and techniques in socially responsible ways (Longley et al., 2015; Unwin et al., 2012). While important, successful execution of technical steps is just one aspect of user–GIS interactivity; a critique of each step, including underlying assumptions, implementation strategy, inputs, and deliverables, is much needed as well (Goodchild & Janelle, 2010).

Although many GIS instructors at institutions of higher learning view GIS software-based exams and projects as the best tools for assessing GIS learning (Matthews & Wikle, 2019), there appears to be some reluctance to give in-class hands-on GIS exams. This is due to factors like: (a) regular lab assignments formatively indicating that students are gaining expected competencies; (b) concerns about technological malfunctions during exams and (i) the uncertainty of resolving them, (ii) their potential impacts on student morale and motivation, or (iii) their implications on individual student exam completion times; plus (c) the definitions, grading, and scoring of acceptable deliverables. The last point alludes to questions about intermediate versus final or well-polished GIS maps, for example. This came up while piloting a version of our summative GAI test, where we found that it is possible for a student to create a powerful choropleth map within 3 min but then spend the next 10 min or more trying to give it a more appealing or professional look and feel. It follows that designing, administering, and grading hybrid GAI tests requires considerable effort and focus.

## 8 | CONCLUSIONS

This study has brought us closer to a holistic GIS education framework. Our framework combines constructs from disciplines like psychology, computer science, and geography to support consistent and persistent delivery of quality GIS education within and across disciplines. It is intuitive, extensible, and in sync with modern views of GIS, plus multimodal ways of mastering this subject. The framework suggests that well-rounded GIS individuals possess both hard and soft geospatial competencies developed and improved through learning GIS by thinking, doing, and feeling within 2D and 3D educational spaces. Since non-geospatial competences are also intentionally developed, these spaces double up as nurturing environments where students can acquire valuable life skills and learn to freely and respectfully express themselves.

The modalities of learning GIS by thinking, doing, and feeling are understood within the contexts of the "circle of GIS thinking," "triangle of GIS practice," and "triangle of affective GIS," respectively. Their outcomes are captured in many geospatial competence models with overlapping and unique KSA. Thus, educators must employ multiple models to define relevant sets of desired GIS learning outcomes. As shown, our GIS learning framework promotes and assists educators in designing hybrid minds-on, hands-on and "body-on" GAI tests to measure student KSA in different courses. Challenges to implementing the proposed GAI include access to sufficient VR devices for individual test takers and inevitable technological glitches which require immediate solution so that students do not panic or become discouraged from completing tests.

Many areas of our study call for further research. These include fully incorporating TAG and TWG elements like modalities for exciting and engaging digital natives experiencing information overload and life distractions in virtually inescapable ways. Also interesting is how to effectively reflect the 2D teaching GIS space in the 2D learning GIS space and strategically embed this area within the greater 3D GIS educational space. Many previous studies on aspects of our work also present opportunities for future research, including: (a) extending DeMers' (2009) work by positioning the GIS&T BoK within the 3D educational space and examining its relative emphasis on cognitive, psychomotor, and affective competencies; (b) building on studies like Prager and Plewe's (2009) to assess how GIS&T curricular fit into the 3D educational space; (c) expanding on Metoyer and Bednarz's (2017) work to conduct classroom experiments on the specific nature of the connections between various thinking modalities (e.g., computational thinking and spatial thinking); and (d) drawing on the work of Xiang and Liu (2018) to examine preferred student learning styles and their impacts on academic performance in different educational domains. Lastly, insofar as there are multiple versions of the GIS BoK that are experiencing widespread use, we have perhaps reached the point where we need to develop an equivalent GIS CoQ (i.e., collection of questions) that is peer reviewed and openly available for adoption and adaptation to create effective classroom assessments.

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## ORCID

*Paddington Hodza* https://orcid.org/0000-0001-5012-3955
*Margo E. Berendsen* https://orcid.org/0000-0003-2934-8855
*Jeffrey D. Hamerlinck* https://orcid.org/0000-0002-7288-6029

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