

A Foundation for Spatial Thinking:  
Towards a Threshold Concept Framework in GIScience and its Implications for STEM Education

by

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## **AUTHOR'S DECLARATION**

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

## **ABSTRACT**

Geographic Information Science (GIScience) is a fairly modern, rapidly emerging multidisciplinary field, addressing the theories and concepts behind the spatial technology called Geographic Information Systems (GIS). With the proliferation of this technology, the demand for GIS professionals has also increased, as has pressure to support their competency in the community of practice. This study investigates a framework of threshold concepts to provide insight into the learning process for distinctive ways of thinking and practising within GIScience. Despite some theoretical investigations of this framework, no empirical studies have explored learner insights on this topic and its implications. The main goal of the study is to investigate empirical evidence of a threshold concept framework in GIScience and its potential implications for Science, Technology, Engineering, and Mathematics (STEM) education.

The investigation relied on data collected through survey questionnaires and personal interviews, administered in an introductory GIS course at the University of Waterloo in Ontario, Canada. The qualitative assessment of the study was based on a phenomenographic approach to examine different ways in which students experience GIS learning. First, threshold concepts were explored and examined based on their transformative, irreversible, integrative, bounded, and troublesome characteristics. In addition, statistical analyses were employed to identify important factors promoting student proficiency in GIScience. These factors were further examined with respect to variations in students' discipline-specific ways of thinking and practising. The implications for STEM education were also discussed, in terms of shared misconceptions, spatial thinking abilities, and academic and career competencies.

Findings from this study suggest that the most prominent threshold concepts perceived by GIScience students are map projections and advantages and disadvantages of raster and vector data models, which are likely to open up new and previously inaccessible ways of thinking (i.e., ways of looking at a map). Important factors for students to acquire an understanding of such concepts were also identified, including academic preparedness, educational status, major field of study, type of academic background, ArcGIS software experience, GIS learning resource, and prior subject learning experience in mathematics, GIS, programming, or computer science. The implications include enhanced spatial thinking ability, as well as creativity, critical thinking, and problem-solving skills, all of which can help to promote interest and self-confidence in pursuing STEM fields. Overall, results from this study offer valuable insights for enhancing the efficacy of teaching and learning in GIScience.

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# CHAPTER 1 INTRODUCTION

This chapter introduces the background of the research problem, explains the significance of this study's contribution, and addresses the research goal and objectives. Then, it outlines the remaining chapters for the overall structure of the thesis.

## 1.1 RESEARCH BACKGROUND

According to Obermeyer and Pinto (2008), there has been growing pressure within the academic community to find a mechanism for educational programs that will support students' professional competency in Geographic Information Science (GIScience). This field is multidisciplinary in nature, addressing the theories and concepts behind the technology called Geographic Information Systems (GIS), which is used for integrating and analyzing spatial data or geographic information. Thus, GIS can "provide a *digital lens* [emphasis added] for exploring the dynamic connections between people ... and changing physical and social environments (Kidman & Palmer, 2006, p. 290). Over the years, this technology has become more affordable and user-friendly, proliferating in both the public and private sectors (Obermeyer & Pinto, 2008). This trend has consequently increased the demand for GIS professionals, as well as the number of GIS users and learners across a wide range of fields (Kemp, 2009; Srivastava, 2013). Along with such expansion and diversification, GIScience educators face a variety of challenges concerned with ensuring a competent, adequately educated and trained workforce of GIS professionals in the community of practice.

To explore such challenges and offer insight into student engagement with learning materials, the notion of *threshold concepts* (Meyer & Land, 2003) has been adopted as a theoretical framework in this current study. Learning threshold concepts is likely to entail troublesome knowledge, which provide useful insight into why many students often become "stuck" at certain points of the curriculum (Perkins, 1999; Meyer & Land, 2006a). Particularly, these concepts are described as "akin to a portal, opening up a new and previously inaccessible way of thinking about something" (Meyer & Land, 2006a, p. 3). Thus, *crossing* thresholds means the acquisition of threshold concepts, helping students to attain "a transformed internal view of subject matter" (Meyer & Land, 2006a, p. 3). This crossing accounts for the progression in the level of learners' disciplinary understanding (Meyer & Land, 2010). An investigation of a threshold concept framework, therefore, provides valuable insight into distinctive ways of thinking and practising within a discipline (Meyer & Land, 2003), as well as its effective teaching and learning strategies (Cousin, 2006a; Land, Cousin, Meyer, & Davies, 2005, 2006). Above

all, GIS learning is a key factor in augmenting students' spatial thinking abilities (Lee & Bednarz, 2009); in addition, its multidisciplinary nature has characteristics for integration of its knowledge and applications in other disciplinary areas (DiBiase et al., 2006; Srivastava, 2013).

## **1.2 STATEMENT OF THE PROBLEM**

Since GIScience is a relatively new field, research on identifying its troublesome knowledge and threshold concepts is fairly limited. Although some theoretical foundations of a threshold concept framework in GIScience have been explored based on expert points of view (e.g., Srivastava, 2013), virtually no empirical studies have provided evidence of this framework from learner perspectives. Particularly, Land, Cousin, Meyer, and Davies (2006) point out that it is difficult for teachers and experienced experts within a discipline "to gaze backwards across thresholds and understand the conceptual difficulty or obstacles that a student is currently experiencing" (p. 199). Moreover, students are from diverse backgrounds, which can affect variation in their learning process or even their performance levels (Land et al., 2006; Meyer & Land, 2003; Srivastava, 2010). In the GIScience community, the question still remains why some students overcome barriers to learning in the discipline with relative ease, while others find difficulty in doing so. Therefore, an empirical evidence gap exists in the knowledge in terms of defining a threshold concept framework in GIScience based on the student perspectives, the role of student characteristics in the process of learning, and the potential implications of crossing thresholds for particular disciplinary ways of thinking.

The findings of this current study, therefore, expect to supplement current knowledge about a threshold concept framework in GIScience, achieved through empirical evidence and insight gained from students undertaking an introductory GIS course at the University of Waterloo, Canada. The empirical evidence of this framework expects to be present based on the key characteristics of threshold concepts (transformative, irreversible, integrative, bounded, and troublesome) proposed by Meyer and Land (2003). In particular, the troublesome and transformative aspects of students' disciplinary understanding in GIScience are to be located in the curriculum. Moreover, since students' prior subject knowledge, aptitudes, and other characteristics are highly varied, this present study also intends to reveal those student factors that are significant for proficient GIS learning. The study then investigates how these student factors may account for variations in overcoming barriers to learning and acquiring threshold concepts. Such findings bear a significant pedagogical importance in curriculum design and development given that they shed light on the ways of supporting teaching and learning (Cousin, 2006a; Land et al., 2006; Osmond, Turner, & Land, 2008). The target audience includes GIScience educators,

advisors, researchers, and practitioners in higher education and research institutions. This present study may identify new opportunities for this target audience (e.g., transforming their own views in teaching, enhancing student preparations in learning).

GIS has gained tremendous popularity over the years, as reflected by the growth of enrollment in GIS courses, the emergence of GIS degree programs/courses in the majority of Canadian universities, and the inclusion of a GIS course prerequisite in many disciplinary programs. Thus, this study has implications not only for the specific course investigated or for the Geomatics Program, but also for the University of Waterloo as a whole and beyond. For example, implications extend beyond GIScience to other Science, Technology, Engineering, and Mathematics (STEM) fields, through their links to shared misconceptions (e.g., Bampton, 2012), spatial thinking abilities (e.g., Lee & Bednarz, 2009), and academic and career competencies (e.g., National Research Council, 2006).

### **1.3 RESEARCH GOAL AND OBJECTIVES**

To fill an empirical evidence gap that exists in the current knowledge about GIScience threshold concepts and their implications for academic and professional practice, the following key research questions are addressed in this study: (1) What are common troublesome knowledge areas and threshold concepts in GIScience? (2) What are the important student characteristics for proficiency in GIScience and how do they account for variations in students' ways of thinking and practising within GIScience? (3) What are the potential implications for GIScience in STEM education?

The main goal of this study is to investigate exploratory empirical evidence of a threshold concept framework in GIScience and its potential implications for STEM education. More specifically, the thesis objectives are the following:

- (i) To explore common troublesome knowledge and threshold concepts identified by GIScience students;
- (ii) To examine variations in students' ways of thinking and practising within GIScience; and
- (iii) To discuss potential implications of threshold concepts and proficiency in GIS learning on other STEM-related fields.

## 1.4 THESIS STRUCTURE

The thesis consists of five chapters. First, **Chapter 1 – Introduction** provides the research background and the statement of the problem, addressing the scope of this study with the specific research goal and objectives. The remaining chapters are structured as follows:

**Chapter 2 – Review of the Literature:** This chapter reviews literature on the theoretical foundations of this study, including the threshold concept framework and its pedagogical significance in GIScience and other implications for STEM-related fields.

**Chapter 3 – Research Design and Methodology:** This chapter describes the framework of the research design and methods employed to answer the research questions and how this study was conducted to achieve research goal and objectives. This chapter also details the development and implementation of the study instrument tools.

**Chapter 4 – Findings and Discussion:** This chapter reports the analysis results based on the quantitative and qualitative data collected through the study instrument tools.

**Chapter 5 – Discussion and Conclusion:** This chapter interprets and explains the key findings and how they answer the research questions of this study. In addition, the limitations of the study are discussed, providing suggestions for future research. This chapter concludes with a reflection on the significance of the research findings and their contributions.

## CHAPTER 2 REVIEW OF THE LITERATURE

This chapter summarizes the literature regarding the threshold concept theory and its values on teaching and learning in higher education. Then, the existing theoretical framework of threshold concepts specific to GIScience is reviewed, as well as the potential implications for GIScience in STEM education.

### 2.1 THRESHOLD CONCEPT FRAMEWORK

#### 2.1.1 Background

The idea of threshold concepts originated in Meyer and Land's (2003) work assessing aspects of student learning in economics, as part of their "Enhancing Teaching–Learning Environments in Undergraduate Courses" project. Since then, the threshold concept framework has become popular and gained recognition across a wide range of disciplinary areas, including biology (Taylor, 2008), computer science (e.g., Zander et al., 2008), economics (e.g., Ashwin, 2008), engineering (e.g., Carstensen & Bernhard, 2008), educational development (e.g., Timmermans, 2014), geography (e.g., Slinger, 2011), mathematics (e.g., Quinnell & Thompson, 2010), and spatial awareness (e.g., Osmond et al., 2008).

Threshold concepts are not necessarily the same as the *core concepts* or *fundamental concepts* typically considered by teachers as being important for a subject (Davies, 2006; Davies & Mangan, 2005). Meyer and Land (2006a) specified that threshold concepts are a subset of core concepts which, once grasped, lead to a transformed view of subject matter. This transformed view may represent "how people 'think' in a particular discipline or how they perceive, apprehend or experience particular phenomena within that discipline" (Meyer & Land, 2006a, p. 3). On the other hand, core concepts "do not necessarily lead to a qualitatively different view of subject matter" (Meyer & Land, 2006a, p. 6); rather, they may act as building blocks that help learners progress in understanding and learning. More precisely, a threshold concept is:

"akin to a portal, opening up a new and previously inaccessible way of thinking about something. It represents a transformed way of understanding, or interpreting, or viewing something without which the learner cannot progress. As a consequence of comprehending a threshold concept there may thus be a transformed internal view of subject matter, subject landscape, or even world view" (Meyer & Land, 2006a, p. 3).

Similarly, Perkins (2006) argued that threshold concepts "act like gateways. Once through the gate, learners come to a new *level* [emphasis added] of understanding [in particular topics] central to the

discipline” (p. 43). This new, deeper level of conceptual understanding may represent ways of thinking and practising that are distinctive to a discipline (Davies & Mangan, 2007; Meyer & Land, 2003). Therefore, mastery of threshold concepts is essential to further progress in a discipline (Meyer & Land, 2003; O’Donnell, 2010).

### 2.1.2 Key Characteristics

As described in Figure 2.1, Meyer and Land (2003) determined that threshold concepts are likely to be *transformative*, *irreversible*, *integrative*, *bounded*, and *troublesome*. These five features are interrelated, as the first three (transformative, irreversible, and integrative) are mutually interdependent and the last two (bounded and troublesome) are derived from the first three (Davies, 2006; Davies & Mangan, 2007).

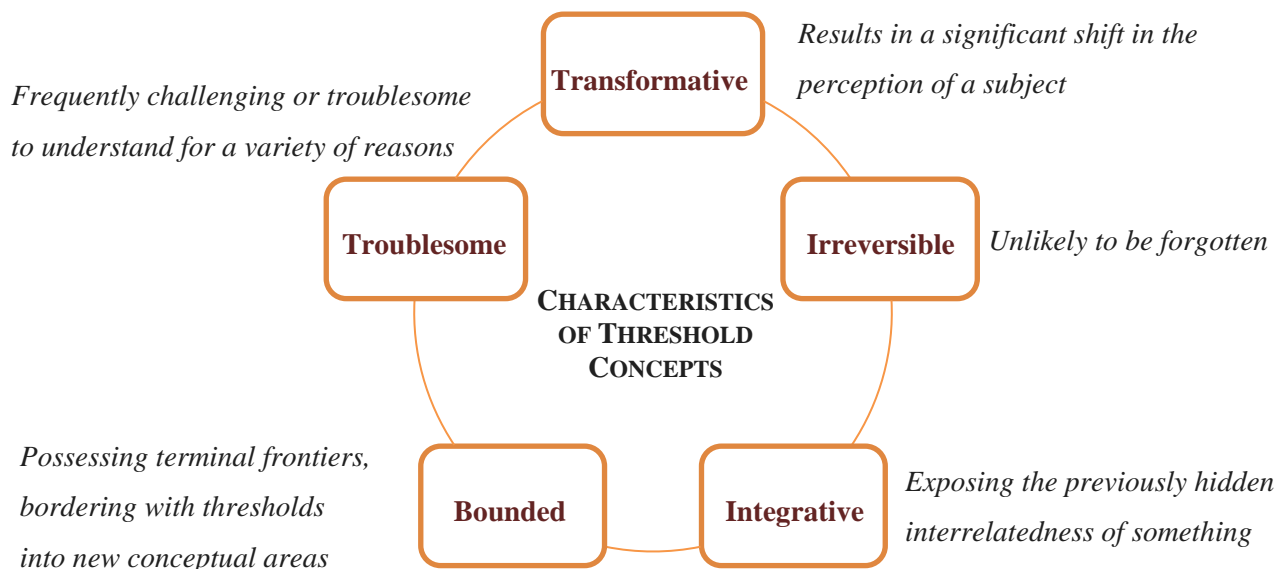


Figure 2.1 – Five key characteristics of threshold concepts.

The three characteristics – transformative, irreversible, and integrative – are mutually interdependent. First, when the crossing of *thresholds* occurs, the transformative quality of threshold concepts reflects the learners’ new ways of thinking and understanding (i.e., through transformation of their perceptions about the subject matter and even the world around them). Such transformation is also linked with the irreversible and integrative qualities of threshold concepts. For example, irreversibility is associated with a significant shift in learners’ conceptual perspectives, making it difficult to return to the way they used to think. Moreover, transformation is accomplished through the integration of learners’ existing and new

knowledge and experiences. Such integration often helps expose previously hidden interrelatedness as a means of making sense of the ideas of a subject that did not make sense before (Davies, 2006; Meyer & Land, 2003).

Furthermore, the bounded and troublesome characteristics of threshold concepts are affiliated with the transformative, irreversible, and integrative features (Davies & Magnan, 2007). For example, the transformed ways of understanding can lead to a privileged or dominant view of a discipline, often defining the boundary of disciplinary conceptual areas or academic terrains (Meyer & Land, 2003, 2005). This bounded feature, also related to the discursive nature of threshold concepts, can be evidenced by the extension of the learners' language use or disciplinary discourse shared particularly within the community of practice (Ashwin, 2008; Meyer & Land, 2003). Thus, this bounded feature is associated with the reconstitution of self in relation to the subject. However, a transformative learning experience can be troublesome because "it requires reconfiguration of previously acquired understanding." (Davies & Magnan, 2007, p. 712). For example, this process can be emotionally uncomfortable or unsettling due to a sense of loss of the previously held conceptual stance (Cousin, 2006b; Meyer & Land, 2003; Savin-Baden, 2008b). The integration process involved in acquiring threshold concepts can also be troublesome if students' previously held conceptual stances or their intuitive belief systems conflict with the new conceptual material being encountered (Meyer & Land, 2005).

In addition, the troublesome criterion of threshold concepts is important for defining their transformative nature. According to Schwartzman (2010), "real learning requires stepping into the unknown, which initiates a rupture in knowing" (p. 38), and such "a significant learning is often troublesome, and indeed needs to be so as to 'provoke' learners to move on from their prevailing way of conceptualizing a particular phenomenon to new ways of seeing" (Land, 2011, p. 176). Thus, the troublesome nature of understanding threshold concepts can provoke, trigger, or stimulate in a way that makes learners realize the sense of transformation occasioned by a significant shift in the perception of a subject and a sense of being (Meyer & Land, 2003; Ricketts, 2010). Therefore, threshold concepts often prove to be troublesome in the learning process (Meyer & Land, 2003, 2005; Perkins, 2006).

### **2.1.3 Forms of Troublesome Knowledge**

The notion of "troublesome knowledge," a potential barrier to students' ability to grasp threshold concepts, was first introduced by Perkins (1999). His work provided useful insight into why many students often become "stuck" at certain points of the curriculum. Perkins (1999) proposed *ritual*,

*inert, conceptually difficult, and alien (or foreign) knowledge*, and Meyer and Land (2003) built upon the work by including *tacit knowledge* and *troublesome language* as other sources of troublesomeness. Meyer and Land (2006a) have suggested that learning threshold concepts is likely to encompass these forms of troublesome knowledge.

Perkins (1999, 2006) has suggested designing appropriate, targeted constructivist methods in response to different forms of troublesome knowledge. Such constructivist methods consider students' learning as the construction of a personalized knowledge that is continuously being refined from an interaction between experience and ideas (Perkins, 1999, 2006; Srivastava, 2012). Based on the work of Perkins (1999, 2006) and Meyer and Land (2003, 2006a), the forms of troublesome knowledge and their constructivist response examples are summarized below:

1. *Ritual knowledge*: This form of troublesome knowledge has “a routine and rather meaningless character” (Perkins, 1999, p. 9). A typical example of ritual knowledge is a diagram used to represent complex relationships in economics. For example, students may have learned and know how to plot a diagram to represent economic relationships, but they may not have understood the mathematical functional complexity that lies behind the representation in this model. A constructivist response to this troublesomeness is to make it more meaningful by facilitating problem-solving activities.
2. *Inert knowledge*: This form of troublesome knowledge is held in the back of one's mind and recalled only when specifically needed (e.g., for a quiz). The use of passive vocabulary (i.e., words that are understood but used only rarely or not used actively) was provided as an example by Perkins (1999). This situation is likely to occur when students simply learn concepts but cannot find relevance to or meaning in the world around them. Thus, this troublesomeness is closely related to the integrative characteristic of threshold concepts (Davies, 2006). A constructivist response is to engage learners in active problem-solving that makes connections to everyday experiences and applications.
3. *Conceptually difficult (or counter-intuitive) knowledge*: This form of troublesome knowledge occurs due to “a mix of misimpressions from everyday experience..., reasonable but mistaken expectations..., and the strangeness and complexity of scientists' views of the matter..., [often resulting in] a mix of ritual knowledge and misunderstandings” (Perkins, 1999, p. 9). For example, McCloskey (1983) observed that learners had difficulties in accepting that “heavier objects fall at the same rate as lighter ones, air resistance aside,” due to the conflict with their

intuitive beliefs and interpretations that heavier objects would fall faster. A constructivist response is to engage students with experiments and observations (e.g., demonstrations), encouraging them to deal with and accept any discrepancies in their intuitive belief systems.

4. *Alien (or foreign) knowledge*: This form of troublesome knowledge “comes from a perspective that conflicts with our own” (Perkins, 1999, p. 10). For example, some learners may struggle to understand issues or value systems carried by others’ different perspectives or cultural mindsets. A constructivist response is to engage learners to identify and compare alternative perspectives in relation to one another. It can be facilitated by compare-and-contrast discussions, dialogues, debates, or role-playing activities.
5. *Tacit knowledge*: This form of troublesome knowledge is often shared within a specific community of practice that remains mainly personal and implicit. That is, the troublesomeness is related to “the *complexity* of the knowledge, its seeming *inconsistency* or paradoxical nature or because it contains *subtle distinctions*, such as that between weight and mass” (Meyer & Land, 2006a, p. 12, emphasis in original). An example of constructivist response is to bring out and examine together all the tacit presumptions that educators and learners have in their minds.
6. *Troublesome language*: This form of troublesome knowledge is concerned with the specific language shared and frequently used within a discipline. Meyer and Land (2006a) argued that specific discourses have been developed within different disciplines, representing distinctive ways of seeing and thinking in their communities of practice. For example, a concept used and understood in one discipline can be very different in another discipline (e.g., jargon). Thus, such discursive practices of a given community may be less familiar and conceptually difficult for new entrants. A potential constructivist response is to provide examples of diverse disciplinary applications.

#### **2.1.4 The Developmental Process of Learning**

Meyer and Land (2006a) described the process of grasping threshold concepts by using the visual metaphor of a *portal* or a *conceptual gateway*. They argued that this metaphor “invites a consideration of how the portal initially comes into view, how it is approached, negotiated, and perhaps even experienced as a transition in terms of sense of self” (p. 19). This process involves a transition through an in-between state of uncertainty, a state of *liminality* (derived from a Latin word *limen* meaning *boundary* or *threshold*), which is not an easy passage to move through because of its troublesome nature. The space or period of such a *rite of passage* that learners undergo to acquire

threshold concepts is referred to as *liminal space* (Meyer & Land, 2006b). Similarly, Bishop (2006, p. 192) described student learning processes as “a journey along a path,” which may involve “times when they are obstructed by a ditch or gully that they will need to cross in order to continue.” Thus, “the most significant aspect of learning lies not in the *outcomes* of learning, but in the *process* of learning” (Timmermans, 2010, p. 3, emphasis in original) in terms of understanding its developmental process.

The learning journey involved in acquiring threshold concepts is illustrated in Figure 2.2, which is developed in this current study by adapting a model of transitional learning spaces (Savin-Baden, 2008a, 2008b) and a relational view of the features of threshold concepts (Land, Meyer, & Baillie, 2010). For example, a notion of *learning spaces* (e.g., disjunctive spaces, liminal spaces, transformational and transitional learning spaces) was proposed by Savin-Baden (2008b) to illustrate the cyclical nature of the journey that learners undergo in the process of acquiring threshold concepts. Furthermore, Meyer and Land (2010) suggested that this learning journey may involve variation in the pre-liminal, liminal, and post-liminal states, helping to identify “at which points, and in what ways, individual students might experience conceptual difficulty and experience barriers to their understanding” (p. 64). With this in mind, each liminal phase is further reviewed in the following sub-sections, delineating the learning journey towards, through, and beyond thresholds.

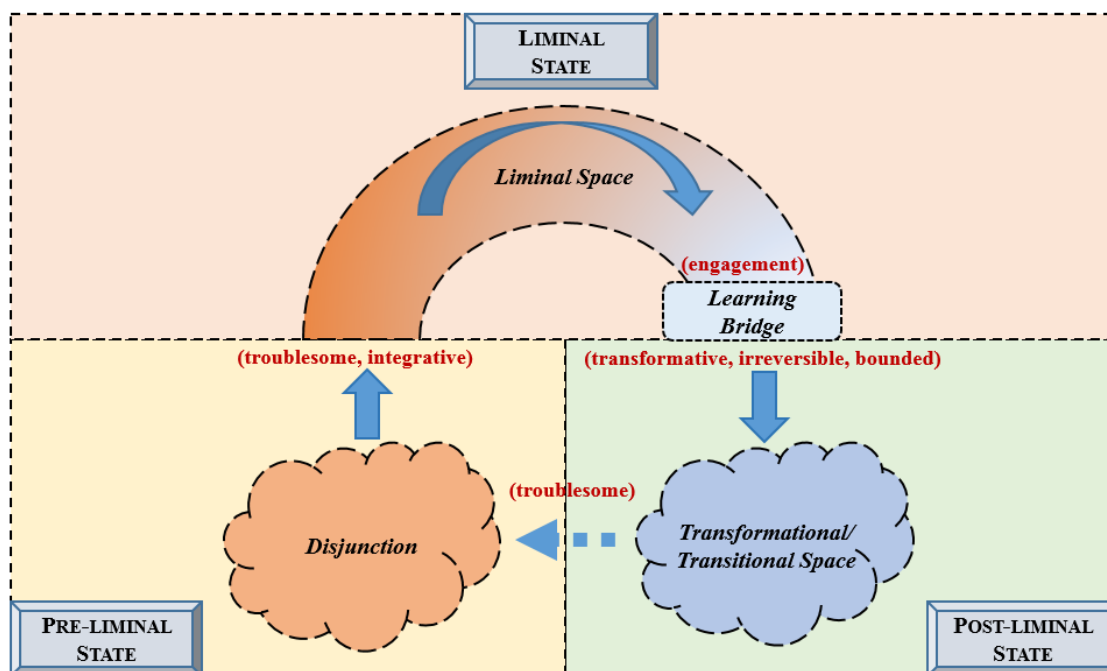


Figure 2.2 – A conceptual model illustrating the process of learning threshold concepts across liminal states [adapted from a model of transitional learning spaces by Savin-Baden (2008b) and from a relational view of the features of threshold concepts by Land, Meyer, and Baillie (2010)].

#### ***2.1.4.1 Pre-liminal State***

The learning journey towards thresholds shown in Figure 2.2 begins with *disjunction*, a space or position where learners initially encounter or realize the troublesomeness of new conceptual materials. Described as “being a little bit like hitting a brick wall” (Savin-Baden, 2008b, p. 81), this state is associated with a form of troublesome knowledge because “it often feels alien and counter-intuitive” (p. 81). In other words, the learner’s impression upon beginning the journey is like *darkness*, making it difficult to find the ways towards thresholds (Orsini-Jones, 2008). Land, Meyer, and Baillie (2010) also claimed that “the journey towards the acquisition of a threshold concept is seen to be initiated by an encounter with a form of troublesome knowledge in the pre-liminal state” (p. ix). Thus, this stage accounts for “a sense of vague stuckness or a feeling of confusion” (Savin-Baden, 2008b), as a threshold concept is first encountered. On the other hand, disjunction “can [also] be seen as the kind of place that students might reach after they have encountered a threshold concept that they have not managed to breach [or conquer]” (Savin-Baden, 2008b, p. 81).

Furthermore, pre-liminal *variation* is concerned with how individual learners perceive a threshold concept in the first place or how it initially “comes into view” (Meyer, 2012; Meyer, Land, & Davies, 2008). This variation depends on different prior tacit knowledge, experiences, or disciplinary backgrounds that learners bring with them (Meyer, 2012; Meyer & Land, 2005, 2006b; Savin-Baden, 2006; Shanahan, Foster, & Meyer, 2008, 2010). For example, Meyer and Land (2005) argued that “as a way of helping students, we can distinguish, in theory at least, between variation in students’ ‘tacit’ understanding (or lack thereof) of a threshold concept” (p. 384). Such student characteristics help to explain the variations associated with “the shifts that are made away from a belief in core concepts and the idea that some knowledge is necessarily foundational to other knowledge” (Savin-Baden, 2006, p. 164). Therefore, understanding students’ pre-liminal variations helps to answer the following questions:

“Why [do] some students ... productively negotiate the liminal space and others find difficulty in doing so [?] Does such variation explain how the threshold will be, or can be, or can only be approached (or turned away from) as it ‘comes into view’? And how does it ‘come into view’ for individual students?” (Land et al., 2006, p. 203).

#### ***2.1.4.2 Liminal State***

As argued by Meyer and Land (2005), liminality is concerned with “the conceptual transformations students undergo, or find difficulty and anxiety in undergoing, particularly in relation to notions of being ‘stuck’” (p. 377). As mentioned earlier, the idea of liminal space is described as the

space or period of the rite of passage towards a threshold (Meyer & Land, 2006b); thus, a liminal space is referred to as the period of oscillation between the old and new states of students' learning stances (Meyer & Land, 2005; Savin-Baden, 2006). Therefore, a liminal space can be considered not only as a "stuck place" (Ellsworth, 1997) but also as a place for "processes of growth, transformation, and the formulation of old elements in new patterns" (Turner, 1967, p. 99).

Moreover, liminal *variation* can occur in the process of how learners enter, occupy and negotiate, and pass through a liminal space (Meyer & Land, 2006b; Meyer, Land, & Davies, 2008).

### *1) Entering into a Liminal Space*

Entering into a liminal space begins with a learner overcoming the first shock of disjunction and re-examining the sense of self (Savin-Baden, 2008b). However, a feeling of confusion may also arise in a liminal space. According to Savin-Baden (2008a), Ellsworth's (1997) "conception of stuck places would seem to imply that stuckness is a place one travels to – whereas disjunction is often a position one seems to find oneself in, often somewhat unexpectedly" (p. 107). Thus, unlike disjunction, a learner may choose to enter into a liminal space by being willing to confront and deal with troublesomeness. In other words, some students may enter into a liminal space at ease and become more readily engaged, while others find doing so problematic because they do not acknowledge the troublesome nature of learning or simply avoid dealing with it (Savin-Baden, 2008b).

Individual students may also bring to the classroom their own preconceptions about the subject matter and how the world works (Bampton, 2012). Such preconceptions can determine how students enter into a liminal space for their engagement. For example, "if their *initial* [emphasis added] understanding is not engaged, they may fail to grasp the new concepts and information that are taught, or they learn them for purposes of a test but revert to their preconceptions outside the classroom" (Bransford et al., 2000, p. 14-15). This statement implies that students' preconceptions or their existing belief systems can affect their *initial* understanding of and engagement with new conceptual materials. In this way, students should be willing to deal with troublesomeness in learning, as doing so will guide them into a liminal space.

### *2) Occupying and Negotiating a Liminal Space*

Meyer and Land (2006b) argued that the process of acquiring threshold concepts involves the occupation of a liminal space, where students oscillate between the old and emergent understandings. In the liminal state, this reconstruction of the sense of being involves the integration of existing and new knowledge and experience (Land et al., 2010). For example, "to understand one concept[,] one might

require some understanding of another” (Ashwin, 2008, p. 181); however, students often “develop their own conception of it, encrusted with previous experiences and metaphors from everyday life, sometimes leading to misconceptions” (Mead & Gray, 2010, p. 98). Such misconceptions can be in the form of incorrect ideas and theories about how the world works, which may hamper students’ ability to grasp threshold concepts (Bampton, 2012; Hestenes, Wells, & Swackhammer, 1992).

More importantly, students who are unable to occupy and negotiate a liminal space are more likely to drop out of or be less competent in a course than those who manage to grasp threshold concepts (Bain & Bass, 2012; Shanahan et al., 2008, 2010). Such consequences are also addressed in Savin-Baden’s (2008a) argument regarding the general trends of coping strategies adopted by students when encountering threshold concepts and finding them troublesome to learn:

“Students may opt to *retreat* from disjunction [withdrawing from any further learning], to *postpone* dealing with it [because they had similar experience and already know how to manage], to *temporize* and thus choose not to make a decision about how to manage it [waiting for an event or stimulus that will help them to progress], to find some means [of circumventing strategies] to *avoid* it and thus create greater disjunction in the long term, or to *engage* with it [directly] and move to a greater or lesser sense of integration” (p. 106, emphasis in original).

In other words, students have different ways of managing troublesomeness when dealing with threshold concepts. Avoidance and retreat may also lead to turning back to disjunction from the liminal space, whereas temporization and postponement may require students to spend some time before they engage in learning and eventually cross the thresholds (Savin-Baden, 2008b). In this regard, those who decide to avoid or retreat will likely drop out of or be less competent in a course (Bain & Bass, 2012; Shanahan et al., 2008, 2010).

In the process of occupying and negotiating a liminal space, the fear of failure and anxiety can bring up the issues of mimicry or lack of authenticity (Cousin, 2006b; Davies, 2006; Meyer & Land, 2005). Such concerns include students undertaking surface learning as a coping strategy (e.g., memorization of facts and routine procedures, reproduction of subject knowledge just to pass a test), which provides only a limited understanding of the underlying meaning of subject knowledge (Entwistle, 2003; McCartney et al., 2009). On the other hand, because students take different paths in dealing with troublesomeness in learning, surface learning can be the first stage for concrete understanding for some students, but be just the opposite for others (Cousin, 2006b; McCartney et al., 2009).

Furthermore, studies have demonstrated that pre-liminal variation can play a crucial role in negotiating a liminal space (e.g., Shanahan et al., 2008, 2010). For example, prior tacit knowledge and experience can provide *bits of knowledge*, helping students to integrate and engage with new conceptual materials for necessary scaffolding and meaningful learning (Davies, 2006; Meyer & Land, 2006a; Savin-Baden, 2008b). Such pre-liminal variation can be coupled with students' recognition of identity in learning, referred to as *learning stances* (Perkins, 2006; Savin-Baden, 2008b). For example, this identity in learning is inherent in "the sense of one's attitude, belief or disposition towards a particular context, person or experience" (Savin-Baden, 2008a, p. 16). All in all, as illustrated in Figure 2.3, individual students enter, occupy and negotiate, and eventually move out of a liminal space differently (i.e., some learners may pass right across, while others may journey back and forth in different ways).

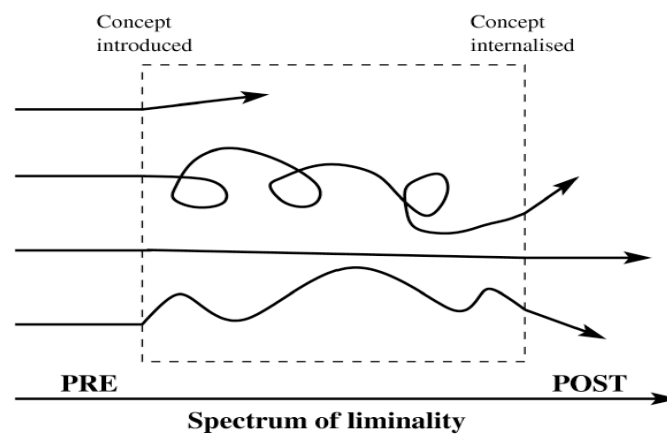


Figure 2.3 – A visual illustration of variation in students' learning journeys through a liminal space (Baillie, Kabo, & Reader, 2012).

### 3) *Moving Through a Liminal Space Towards a Transitional/Transformational Space*

Land et al. (2010) argued that the process of moving through a liminal space "requires a reconfiguring of the learner's prior conceptual schema and a letting go or discarding of any earlier conceptual stance" (p. xi). Savin-Baden (2008b) suggested that the most effective way of helping students to cross thresholds or move out of a liminal space may involve locating a *learning bridge*, which refers to *engagement* for developing greater self-understanding. In other words, learning bridges are mechanisms that "help to link or connect different past and present positions in ways that enable shifts" (p. 85) from the liminal state to the post-liminal state. Such mechanisms should encourage students "to analyze a new context, identify similarities that might enable them to pull from past knowledge and experience, and consciously adapt to differences" (Moore, 2012, p. 23).

Baillie and Johnson (2008), however, asserted that the fear of the unknown in a liminal space can act as a barrier to engagement. Cousin (2006) also proposed that emotional capital (e.g., learner anxiety) can

affect mastery of threshold concepts. For example, some factors (e.g., age) may affect different life experiences that individuals can draw from in relation to their learning. Studies have also shown that students' different levels of confidence or feeling of knowing (i.e., dependent on their prior knowledge and academic preparation) can affect their engagement in learning (Efklides, 2006; Quinnell & Thompson, 2010). One way to overcome the barrier to engagement is "learning to live with tensions ... that may occur in the process of gaining greater self-understanding and acquiring new ways of thinking ... [and] not eliminat[ing] but learn[ing] to value doubt and uncertainty as central principles of learning" (Savin-Baden, 2008b, p. 83). Thus, students' anxiety should be addressed rather than avoided, so that they can confront and attempt to deal with it (Baillie & Johnson, 2008; Savin-Baden, 2008b).

#### ***2.1.4.3 Post-liminal State***

Acquisition of threshold concepts leads to new ways of thinking and practice that are specific to a discipline. This acquisition involves ontological and epistemic shifts in a transformational/transitional learning space (Meyer & Land, 2003; Savin-Baden, 2008b). The movement from liminal to post-liminal state induces a sense of moving from one place to another, achieved through learners' identity construction, self-realization, and transformation (Davies, 2006; Meyer & Land, 2003; Savin-Baden, 2008b). Thus, acquiring a threshold concept is an act of identity formation or perspective transformation (Davies, 2006; Meyer & Land, 2003) associated with "a change in sense of self, a change in subjectivity on the part of the learner" (Land & Meyer, 2010, p. 72). This development is "an irreversible transformation and is marked by a changed use of discourse" (Land et al., 2010, p. xi).

Post-liminal variation contributes to how individuals may achieve a particular way of thinking and practising within a discipline (Davies, 2006). This variation also accounts for "students' *level* [emphasis added] of new conceptual understanding" (Meyer & Land, 2010, p. 63), which "may involve a 'performance element'" (Meyer & Land, 2003, p. 4). For example, the transformative nature of threshold concepts may enable students to open up "a new and previously inaccessible way of thinking" (Meyer & Land, 2003, p. 1) for the progression of their understanding of conceptual materials.

Davies and Mangan (2006, 2007, 2008) argued that acquiring a threshold concept involves different but mutually interdependent types of transformation. The first type, *basic conceptual change*, is related to "naïve or 'common-sense' understanding supplemented by a more powerful discipline-based mode of thinking" (Davies & Mangan, 2007, p. 713). This transformation is associated with the integration of newly met disciplinary concepts/ideas and students' personal experience in the world around them. Another type of transformation is called *discipline-based conceptual change*, which involves the

integration and re-working of other disciplinary concepts or ideas that the learner already possesses. Finally, *procedural conceptual change* is also a transformation type, which involves constructing discipline-specific narratives and arguments (i.e., acquiring granted or particular ways of thinking and practice shared in a subject community).

As mentioned earlier, the transformative nature of threshold concepts, however, may sometimes be emotionally uncomfortable, unsettling, or disturbing, due to a sense of loss of previously held conceptual stances (i.e., leaving a familiar position and moving to a new and less certain terrain) (Cousin, 2006b; Meyer & Land, 2003; Savin-Baden, 2008b). In addition, as students encounter different conceptual materials, the new established learning stances and ways of thinking can be part of another disjunction, continuing in the cyclical process of the learning journey.

## **2.2 NARROWING DOWN POTENTIAL THRESHOLD CONCEPTS**

The idea of threshold concepts initially arose from concerns associated with supporting students who tend to get stuck at particular points of the curriculum in a discipline (Meyer & Land, 2003, 2005). With a similar motivation, the methodology of *Decoding the Disciplines (DtD)* was developed by Middendorf and Pace (2004). During the process of developing DtD methodology, a number of scholars met in a series of group seminars and discussed common learning barriers (also known as *bottlenecks*) that students tend to face in their disciplinary fields. In discussing how to devise ways that can help students to overcome bottlenecks, they proposed the following seven steps of DtD: (1) identifying the bottlenecks to learning in class; (2) exploring how experts in the field overcome these bottlenecks (e.g., through skills, approaches, procedures); (3) determining how these tasks may be explicitly modelled, applied, and incorporated in instruction and teaching practices; (4) providing opportunities for students to practice these adapted approaches and to receive feedback; (5) motivating students with respect to why they are employing such practices; (6) assessing how well students are mastering those approaches to overcome the bottlenecks; and (7) sharing any lessons learned from the previous steps among faculty to suggest necessary institutional changes.

The DtD methodology is a useful approach to explore threshold concepts within a discipline. Middendorf and Pace (2004) argued that bottlenecks can be potential indicators of which areas of disciplinary thinking are not made clear to students. In other words, these difficulties of bottlenecks may arise from students failing to fully understand a threshold concept (Shopkow, 2010). This idea can help to distinguish those who are “inside” the subject and those who have not yet gained that way of disciplinary thinking (Davies, 2006). More importantly, bottlenecks themselves “may be threshold

concepts ... [or] clusters of threshold concepts ... [that] constitute disciplinary ways of knowing” (Shopkow, 2010, p. 327); therefore, concepts that are central to a discipline but often prove to be troublesome are a good place to begin narrowing down potential threshold concepts (Bampton, 2012; Cousin, 2006b; Cowart, 2010; Davies & Mangan, 2007; Male & Baillie, 2011; Meyer & Land, 2003; Ross, 2010; Zander et al., 2008). As such, troublesome and transformative characteristics are widely used in the process of identifying threshold concepts (e.g., Male & Baillie, 2011; Zander et al., 2008).

Moreover, the DtD methodology itself offers opportunities for teaching and learning (Díaz, Middendorf, Pace, & Shopkow, 2008; Meyer & Land, 2005; Shopkow, 2010). For example, Shopkow (2010) recommended that this methodology can offer and facilitate the following:

- Identifying concepts and understandings which may be related to threshold concepts;
- Revealing the troublesome nature of threshold concepts (e.g., tacit knowledge);
- Providing guidance to re-examine and re-evaluate instructors’ own teaching practices;
- Re-designing lessons to support students’ learning experiences; and
- Motivating intervention among faculty within and across disciplines to encourage any necessary institutional changes to guide students in achieving shared learning goals.

Shopkow (2010, p. 329) further highlighted the importance of the last point about collaboration among faculty regarding a threshold concept approach in DtD:

“The impediments to our students learning one threshold concept arise from their difficulties with another, perhaps one they have never encountered. ... We need collaboration within disciplines because we have a shared charge in educating our students and we need collaboration across disciplines not only because there are common problems we might confront ... but also because it can clarify for us what thresholds our discipline might be constructing ... as we consider other thresholds shaped by other disciplines within the shared architecture of higher education.”

This statement implies that students’ prior knowledge and experiences from other disciplines can also play a crucial role in shaping and crossing the thresholds for any associated transformative learning. This implication also articulates the threshold concept research work by Barradell (2012) and Cousin (2008) regarding *transactional curriculum inquiry* (i.e., exploring the difficulty of a subject by mediating educator’s knowledge, students’ learning experience, and educational developers’ help). Therefore, the threshold concept framework provides an opportunity to open up dialogue and collaboration among students, academic researchers, and teaching staff in developing curricula and facilitating teaching and learning (Cousin, 2008; Cousin, 2010; Osmond et al., 2008).

## 2.3 COURSE CURRICULUM DESIGN AND DEVELOPMENT CONSIDERATIONS

This section highlights the implications of the threshold concept framework on teaching and learning in higher education. These implications are assessed with respect to the following key considerations (e.g., Land et al., 2005, 2006): (1) the “jewels” in the curriculum, (2) sequence of threshold concepts in teaching, (3) the importance of engagement, (4) listening for understanding, (5) recursiveness and excursiveness, (6) supportive liminal environment for tolerating confusion and uncertainty, (7) the role of pre-liminal variation, (8) unintended consequences, and (9) the underlying game.

### *1) The “Jewels” in the Curriculum*

Threshold concepts can be viewed as “jewels” in curricula because these concepts can serve as powerful transformative and meaningful areas in the developmental process of learning for a discipline. For example, Meyer and Land (2006a) contended that “where threshold concepts exist within curricula[,] there is likelihood, owing to their powerful transformative effects, that they may prove troublesome for students” (p. 16). Thus, threshold concepts can play a diagnostic role in alerting educators, course instructors, or tutors to areas of the curriculum where students are likely to get stuck. In this regard, threshold concepts may offer a “less is more” approach by encouraging educators to focus on those jewels in the curriculum (e.g., key areas that need mastery for richer insights into the subject) (Cousin, 2006a; Meyer & Land, 2010). However, it is important to note that concentrating only on threshold concepts in teaching can lead to students becoming obsessed with them to the exclusion of other concepts. This blinkered approach may ultimately not help improve students’ comprehensive understanding of subject matter (Entwistle, 2008; Reimann & Jackson, 2006).

### *2) Sequence of Threshold Concepts in Teaching*

Instruction and course curricula should also consider the sequence of threshold concepts in order to foster students’ integrative understanding (e.g., Carstensen & Bernhard, 2008). For example, if threshold concepts are introduced too early, students may not be able to fully grasp them due to a lack of fundamental understanding (Davies, 2006). In this respect, Davies (2006) suggested that fundamental concepts should be introduced at the beginning of the course so that learners can first acquire necessary bits of knowledge and have time to process them. These bits of knowledge can integrate and consequently serve as foundational building blocks to foster meaningful learning in the process of moving through a liminal space. However, students may still struggle to truly “get inside” the subject if their existing bits of knowledge are not re-constructed or re-interpreted in the process of learning

threshold concepts. For this reason, both teaching sequences and students' engagement are important in the context of learning threshold concepts (Carstensen & Bernhard, 2008).

### *3) The Importance of Engagement*

As mentioned earlier, a learning bridge or a mechanism for engagement, helps learners shift from a liminal space to a transformational/transitional space, causing transformation with respect to subject matter. For this mechanism, educators can help students to engage in conceptual materials by encouraging them “to explain it, to represent it in new ways, to apply it in new situations and to connect it to their lives” (Land et al, 2006, p. 199). For example, learning by doing or active participation (i.e., experiential learning) can promote an understanding of abstract principles (Davies, 2006). This approach can further be enhanced if the theory-practice gap is reduced by linking between conceptual materials covered in lectures and practical exercises arranged in lab tutorials (Kinchin, Cabot, & Hay, 2010). In addition, reflective examination activities can be used to help students foster their engagement (Davies & Mangan, 2008; Moore, 2012; Schwartzman, 2010). In particular, they can support the integrative and transformative nature of learning threshold concepts (Moore, 2012) by dynamic engagement between students' internal processes and conceptual materials being covered (Schwartzman, 2010).

### *4) Listening for Understanding*

Because acquiring threshold concepts involves perspective and conceptual shifts, the new way of thinking is irreversible or unlikely to be forgotten (Eckerdal et al., 2006; Meyer & Land, 2006b). Subsequently, teachers or experts find it difficult to retrace the journey back across thresholds and reflect on their past troublesome and transformative learning experiences (Cousin, 2006b; Meyer & Land, 2006a; Ricketts, 2010). Attempts by teachers or expert to retrace and reflect so as to understand untransformed student perspectives become even more challenging if their crossing of thresholds occurred a long time ago (Meyer & Land, 2006a). Therefore, the acquisition of a “third ear” (i.e., through listening to and interiorizing learners' feedback and comments) will be helpful in assessing current challenges or uncertainties that students may be facing (Cousin, 2006b; Felton, 2013; Land et al., 2006). Furthermore, understanding student perspectives can consequently transform teachers' perspectives with respect to the ways of teaching or delivering course content (Meyer, 2012).

### *5) Recursiveness and Excursiveness*

The complexities of learning that students may undergo should also be acknowledged. The troublesome nature of threshold concepts makes learners likely to take recursive steps, journeying back

and forth in liminal spaces until the integration necessary for engagement takes place. Evidently, students do not learn threshold concepts in a simple and/or linear approach. It is also important to note that learning is excursive; that is, students can digress or deviate from an intended direction or outcome (i.e., revisiting the eventual destination to be reached in learning journeys). The recursive and excursive nature of learning is visually illustrated in Figure 2.3 on page 14. Some learners may pass right through in a straight forward fashion, while others may journey back and forth in different ways.

#### 6) *Supportive Liminal Environment for Tolerating Confusion and Uncertainty*

Land et al. (2006) recommended provision of a *supportive liminal environment*, originally referred to as a *holding environment* by Winnicott (1971), to help students withstand and tolerate confusion and uncertainty involved in troublesome learning experiences. For example, a supportive liminal environment can be created through interaction between learners and teachers/tutors (i.e., sharing feedback or reflections on ongoing difficulties in learning) (Cousin, 2008). A form of peer assessment can also be used to help students discover and share common difficulties and anxieties that they are retaining. According to Savin-Baden (2008a), such supportive liminal environments are promised to “convince students to step outside their comfort zones and enter zones of uncertainty, while supporting their endeavours through the provision of adequate learning resources and technologies as well as access to enhanced *student-teacher interaction* [emphasis added]” (as cited in Gnaur & Hüttel, 2014, p. 221).

#### 7) *The Role of Prior Content Knowledge as Pre-Liminal Variation*

As detailed in Section 2.1.4, pre-liminal variations include students’ prior knowledge and experience. Kinchin, Cabot, and Hay (2010) argued that “the determination of prior knowledge is essential to understand how a particular student may *approach* [emphasis added] a particular threshold – the trajectory of approach being influenced by what is already known” (p. 91). Thus, identifying necessary prior knowledge for students’ scaffolding learning can help them productively occupy, negotiate and move through liminal spaces (Meyer & Land, 2003, 2006; Reimann & Jackson, 2006; Savin-Baden, 2008b). In the field of GIScience, students’ prior programming, mathematical, and statistical knowledge were proposed as necessary prior knowledge or learning experiences to perform advanced GIS analyses (Srivastava, 2013). Furthermore, students from engineering and information and technology programs were found to be more successful in GIS assessment tasks (i.e., applying GIS to real-world problems), due to their existing computer and programming-related knowledge and experience (Srivastava, 2010). Other studies (e.g., Bampton, 2012; Sui, 1995) also argued that physical geography is foundational knowledge to students’ understanding of GIScience. Nevertheless, “if ...

everything appears familiar already, the environment is unlikely to provide sufficient stimuli for students to review and revise their existing knowledge” (Reimann, 2004, p. 20). For example, Reimann (2004) found evidence that, if a threshold concept was already familiar, students considered it as a “revision rather than stimulating them to re-evaluate their pre-existing knowledge and conceptualizations” (p. 26).

#### 8) *Unintended Consequences of Generic Good Pedagogy*

Due to the troublesome nature of threshold concepts discussed earlier, educators and course designers may consider *good pedagogy* as a means of simplifying the complexity of these concepts. However, such an attempt can be dysfunctional for students. For example, Shanahan and Meyer (2006) argued that simplifying threshold concepts may act as a barrier to learning by leading to a ritualized (i.e., routine and meaningless) form of troublesome knowledge. Similarly, Land et al. (2006) also argued,

“The simplified interpretation of the concept, intended to some extent as a proxy for the fuller, more sophisticated understanding which it was intended to lead on to, was found to operate more frequently as a false proxy, leading students to settle for the naive version, and entering into a form of ritualized learning or mimicry” (p. 203).

Moreover, relating concepts to everyday phenomena is sometimes ineffective, particularly for first-year students because they have relative lack of relevant experiences (Land et al., 2005, 2006).

#### 9) *The Underlying Game*

Perkins (2006) argued that “disciplines are more than bundles of concepts” (p. 41-42) that complement and operate together to establish distinctive ways of knowing (i.e., “the whole is more than the sum of its parts” as originally coined by the philosopher Aristotle), also known as the *underlying game* or *episteme* (Carstensen & Bernhard, 2008; Land et al., 2005, 2006; Land et al., 2010; Mead & Gray, 2010; Perkins, 2006). More specifically, an episteme can be defined as “a system of ideas or way of understanding that allows us to establish knowledge” (Perkin, 2006, p. 42). An episteme can also be considered as “a common feature of the process of entry, meaning making and identity formation typically required for entry to a given community of practice” (Land et al., 2010, p. xi). Since threshold concepts do not operate as discrete or separate entities, an episteme of a subject may explicitly evolve through making their links in a web fashion, known as a *web of concepts* (Davies & Mangan, 2005, 2007, 2008). Thus, concept-mapping (Novak, 1990) can be used as a graphical or visual representation tool to organize knowledge so as to reveal the links or relationships between various concepts or students’ understanding, thinking, and ideas (e.g., Kinchin et al., 2010; Wheeldon & Faubert, 2009).

## 2.4 THEORETICAL FOUNDATION FOR THRESHOLD CONCEPTS WITHIN GISCIENCE

The major development of a GIScience curriculum framework has been led by several organizations over the years, including the Geographical Information Science and Technology Body of Knowledge (GIS&T BoK) (DiBiase et al., 2006), the US-based National Center for Geographic Information and Analysis (NCGIA) (NCGIA, 2000), and the Core Curriculum in GIScience (Kemp & Goodchild, 1992). Meyer and Land (2006a) argued that “threshold concepts would seem to be more readily identified within disciplinary contexts where there is a relatively greater degree of consensus on what constitutes a body of knowledge” (p. 15). A degree of consensus on a body of knowledge has arguably been identified in GIScience. For example, the GIS&T BoK was designed and developed by more than 70 educators, researchers, and practitioners (DiBiase et al., 2006). This publication provides key knowledge areas and a set of key concepts (e.g., 10 knowledge areas, consisting of 73 units, with over 1600 educational objectives), which are central to the discipline and agreed upon in the subject community.

In so far, the theoretical foundation of threshold concepts within GIScience has been described by Srivastava (2013). This foundation was explored through summative content analysis of seminal GIS research papers based on available resources from the GIS&T BoK and NCGIA. The analysis involved counting the number of matched pre-defined codes of GIS concepts and topics within 28 selected seminal research papers (i.e., from 14 different journals) published between 1968 and 2010. The most matched pre-defined codes were in order of interoperability, data models, and map scale. Srivastava (2013) concluded that these were GIS threshold concepts that students needed to master in order to become expert GIS users (i.e., being able to address real-world issues using GIS).

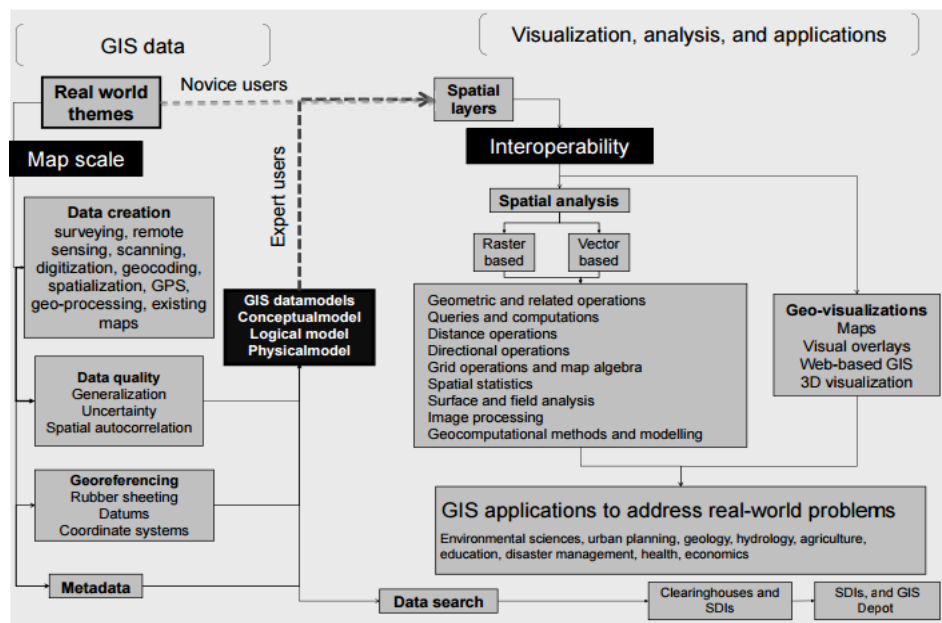


Figure 2.4 – The integrative nature of GIS threshold concepts (black boxes) with other concepts (Srivastava, 2013).

### 1) *Interoperability*

Interoperability is associated with spatial analysis performed by other tools from different disciplinary areas, such as mathematics and statistics (e.g., spatial statistics, data mining, data models, and network analysis) (DiBiase et al., 2006; Srivastava, 2012, 2013). Students with some knowledge of programming, mathematics and statistics are likely to utilize the integrative and analytical power of GIS tools more effectively (Srivastava, 2012). Students' understanding of interoperability may initially be troublesome due to its different levels of hierarchy and meanings. However, once this troublesomeness is overcome, students may transform their ways of understanding with respect to integrating and applying the spatial component of GIS with other disciplinary knowledge (Srivastava, 2013). Such transformation also reflects integrative and irreversible characteristics of threshold concepts, since students *begin* to consider exploring different ways of extending GIS applications with other disciplinary domains (e.g., programming, mathematics, and statistics). By being able to perform more-advanced GIS analyses, students may also extend subject-specific language use (e.g., technical terms related to GIS spatial tools) as a means of entering a conceptual terrain distinctive to the subject community (i.e., bounded feature of threshold concepts).

### 2) *Data Models*

Representation of space or real-world geographical features is referred to as data models (Peuquet, 1984). The two types of data models used for representing real-world features are called rasters (e.g., cell-based systems or resolutions) and vectors (e.g., points, lines, and polygons). Each type has its own assumptions and implications for spatial analysis and representation. Students may find data models difficult to understand because of their underlying assumptions behind map representations. Once this difficulty is overcome, students may transform their ways of understanding with respect to the appropriate use of each data model (Srivastava, 2013). As students *begin* to consider such appropriateness, this new way of thinking is irreversible and unlikely to be forgotten. Srivastava (2013) further argued that the understanding of data models is integrative with other key GIS concepts (e.g., map scale, errors and uncertainty, metadata, queries, overlaying) for the progression of disciplinary understanding. As for the bounded feature of this threshold concept, students may extend their language use or technical terms related to the abstractions of data models representing real-world features.

### 3) *Map scale*

The term *map scale* in cartography means “the representative fraction, which is the ratio between the real world and the map representation” (Srivastava, 2013, p. 373). In other words, map scale can control the levels of abstraction (e.g., generalization, exaggeration) as well as uncertainty and

positional accuracy (Goodchild, 2000; Goodchild & Proctor 1997). Thus, map scale can be linked to other key GIS concepts in terms of the analysis and visualization of geographic information (Srivastava, 2012, 2013). On the other hand, Srivastava (2012, 2013) argued that map scale can be difficult to understand at first because the term *scale* is widely used with different meanings across various disciplines. Once this troublesomeness is overcome, students may transform their ways of thinking about the subject matter, such as being more cautious about *data quality*. Based on the particular needs of a real-world issue, these students may *begin* to consider selecting the most appropriate map scale for analysis and visualization. By recognizing such importance, students may also adopt and apply the use of technical language (e.g., resolution) relevant to GIScience.

## **2.5 IMPLICATIONS FOR GISCIENCE IN STEM EDUCATION**

STEM education refers to teaching and learning in the fields of science, technology, engineering, and mathematics (Gonzalez & Kuenzi, 2012). Several studies have argued that GIScience may be applicable to STEM disciplines through their theoretical links in the context of shared misconceptions (e.g., Bampton, 2012), spatial thinking abilities (e.g., Lee & Bednarz, 2009), and academic and career competencies (e.g., National Research Council, 2006).

### *1) Misconceptions Shared by GIScience and STEM Students*

Misconceptions, incorrect ideas that students retain, can be a barrier to learning in the process of moving through liminal spaces (Bampton, 2012; Bishop, 2006; Hestenes, Wells, & Swackhammer, 1992; Mead & Gray, 2010). More importantly, “timely intervention and curricula designed to target misconceptions help students master threshold concepts and resolve the difficulties posed by troublesome knowledge” (Bampton, 2012, p. 118). In reviewing the literature on other STEM education research, Bampton (2012) found that a significant number of misconceptions in STEM-related disciplines matched core concepts that formed the theoretical underpinnings of GIScience in textbooks (e.g., Lo & Yeung, 2007), model curricula (e.g., UCGIS, 2003), and the GIS&T BoK (DiBiase et al., 2006). The findings indicated that the STEM disciplines whose misconceptions matched most frequently with those of GIScience were as follows: math and statistics, computer science, geography, engineering, and physics. These matched misconceptions were under the following topics of the BoK: analytical methods, design aspects, data modeling, geospatial data, and geocomputation.

Misconceptions in GIScience that are relatable to other STEM-related disciplines, for example, include *projections* and *coordinate systems* (Anderson & Leinhardt, 2002; Skordoulis, Vitsas, Dafermos, & Koleza, 2009). First, studies have showed that novice GIS learners (i.e., those who have not yet entered

the academic terrain) had more difficulties in grasping these concepts (e.g., Anderson & Leinhardt, 2002; Bampton, 2012; Downs & Liben, 1991). In geography, these concepts are crucial to “establish the framework of geometric correspondence between map and reality” (Downs & Liben, 1991, p. 313). More specifically, Gregg and Leinhardt (1994) noted, “understanding projection allows a map reader to understand the ways in which the symbol system has been distorted to accommodate the round surface of the earth as it is transformed to fit onto a two-dimensional place” (as cited in Anderson & Leinhardt, 2002, p. 289). In addition, a coordinate system “is a piece of knowledge giving answers to problems related to classical analytic geometry and provides the framework for the formulation of differential equations that can solve specific Geometric or Physics problems” (Skordoulis, Vitsas, Dafermos, & Koleza, 2009, p. 265). Considering such capabilities, their misconceptions are associated with the distorted size and shapes of the Earth’s surface features as well as the relative location of land masses (Anderson & Leinhardt, 2002). Furthermore, in mathematics, projections and coordinate systems are related to *dimensions* (e.g., estimating the dimension of a horizontal line segment, determining the curve’s dimension), which also prove to be troublesome for students (Skordoulis, Vitsas, Dafermos, & Koleza, 2009). Another example of shared misconceptions is *uncertainty*. In GIScience, understanding uncertainty and error (i.e., behind the visualization of real-world features on a projected map) are often found to be troublesome for novice learners (MacEachren et al., 2005; Srivastava, 2013). Similarly, this troublesomeness is related to recognizing underlying sources of error in chemistry and physics (e.g., Carbó, Adelantado, & Reig; Deardorff, 2011) and simulation and modelling in engineering (Trevelyan, 2014). In particular, arbitrary evaluations of results without reporting uncertainty and underlying sources of error are problematic for students (MacEachren et al., 2005). *Data manipulation* is another shared misconception area between information sciences (e.g., a database language like SQL) and GIScience (e.g., a relational database management system) (Bampton, 2012; Mitrovic 1998).

As shown in the aforementioned examples, a number of misconception areas are shared by GIScience and STEM students; thus, the areas of difficulty in their learning may also be similar (Bampton, 2012). In other words, any lessons learned from helping students to overcome those similar misconceptions can be applied to promote both GIScience and STEM education.

## 2) *Relationship Between GIS Learning and Spatial Thinking Abilities*

According to *Learning to Think Spatially* (National Research Council, 2006), spatial thinking is “a constructive amalgam of three elements: concept of space, tools of representation, and process of reasoning” (p. 25). In the context of GIScience, spatial thinking plays a crucial role in recognizing, visualizing, comprehending, and analyzing *spatial features, distributions, and relationships* (Albert &

Golledge, 1999; Gersmehl & Gersmehl, 2006). Noting the existence of the relationship between GIScience and spatial thinking abilities, studies have showed that acquiring GIS knowledge and skills can improve students' spatial thinking abilities (Huynh, 2009; Lee & Bednarz, 2009; National Research Council, 2006; Srivastava, 2010).

Critical spatial thinking is what goes on in the minds of experienced or competent GIS users (Goodchild & Janelle, 2010; National Research Council, 2006; Wakabayashi & Ishikawa, 2011). Other studies also argued that GIS learning can establish a "geographic foundation of thinking spatially" (Sinton, 2015) or "spatial thinking as a conceptual foundation" (Wakabayashi & Ishikawa, 2011). With this in mind, some studies have applied and examined the threshold concept theory to the promotion of students' geographic foundation of thinking spatially (e.g., Slinger, 2011; Srivastava, 2013). For example, Slinger (2011) argued that transformative learning in geography-related education may entail the following: enhanced use of geographical terminology integrated with everyday experiences, organization of ideas and concepts in making sense of real-world geographical problems, and geographical thinking involved in ways of practising. Other studies have also demonstrated that understanding how maps represent the surface of the Earth (i.e., being able to see through the map to the real world behind it) is a component of geographic expertise shared within the subject community of practice, and that novices are not capable of doing so (Anderson & Leinhardt, 2002; Downs & Liben, 1988). These examples reflect the key characteristics of threshold concepts (e.g., changed ways of thinking, integrated relevant experiences, extension of disciplinary-specific discourse), as detailed in Section 2.1.2. Similarly, Osmond, Turner, and Land (2008) examined the notion of *spatial awareness* in Transport and Product Design. According to Gardner (1983), the implications of crossing such a threshold include the perspective and conceptual transformations with respect to geographic reasoning:

"Central to spatial intelligence are the capacities to perceive the visual world accurately, to perform transformations and modifications upon one's initial perceptions, and to be able to re-create aspects of one's visual experience, even in the absence of relevant physical stimuli ... spatial intelligence emerges as an amalgam of abilities. The most elementary operation, upon which other aspects of spatial intelligence rest, is the ability to perceive a form or an object ... *appreciating* [emphasis added] how it will be apprehended for another viewing angle, or how it would look (or feel) were it turned around" (as cited in Osmond et al., 2008, p. 245).

Therefore, the literature implies that threshold concepts in GIScience can also potentially open up a new way of thinking about the subject matter, refining students' spatial or geographic perspective (i.e., ways of looking at maps or critical spatial awareness) (Kerski, 2012; Srivastava & Tait, 2012).

### 3) *Increasing Student Interest and Success in Academia and Careers in STEM Fields*

Several studies highlighted that students' enhanced spatial or geographic perspective is positively associated with their interest and success in STEM disciplines (Baker, 2012; Kerski, 2012; National Research Council, 2006; Newcombe, 2010; Sinton, 2012). For example, "being able to visualize, analyze and interpret spatial information is fundamental to content understanding and problem-solving, especially in STEM disciplines" (Sinton, 2012, p. 22). The National Research Council 2006 report also highlighted that students' use of geospatial technology can promote their spatial thinking and competencies for STEM fields.

Some of the key competencies include creative thinking, problem-solving, and capability of working with tools and technology. For example, "students who are well grounded in the spatial perspective through GIS are better able to ... think systematically ... [and] make use of the inquiry process ... to solve problems" (Kerski, 2012, p.5). Thus, these competencies can promote students' success in STEM disciplines, including astronomy (e.g., relating the celestial sphere to the structure of the universe), biochemistry (e.g., visualizing DNA or the molecular structure of a cell), Earth science (e.g., diagnosing Earth features and processes), geoscience (e.g., recognizing a shape or pattern), mathematics (e.g., dealing with lines, planes, points, polygons, and symmetry), and physics (e.g., perceiving physical properties and transformation) (National Research Council, 2006). Other studies also showed that spatial thinking abilities can play a crucial role in other STEM-related disciplines, including chemistry (e.g., Tuckey, Selvaratnam, & Bradley, 1991), engineering (e.g., Miller-Young, 2010), geography (e.g., Gregg & Leinhardt, 1994), and programming (e.g., Tai, Yu, Lai, & Lin, 2003).

Therefore, students' spatial thinking abilities and competencies developed through GIScience education can provide greater employment opportunities in STEM fields (Gewin, 2004). For example, students with GIS competence are "primed for STEM-based careers [such] as wildlife biologists, soil scientists, seismologists, geographers, program managers, landscape architects, civil engineers, environmental scientists, and in hundreds of other positions" (Kerski, 2012, p. 2). Particularly, competence levels are more critical to those professions which demand recognition of complex patterns and/or of two- or three-dimensional spatial configurations (National Research Council, 2006).

According to Longley, Goodchild, Maguire, and Rhind (2011, p. 227), "geographic data modelling is *both an art and a science* [emphasis added]. It requires a scientific understanding of the key geographic characteristics of real-world systems, including the state and behavior of objects, and the relationships between them." All in all, students' spatial thinking ability, as well as creativity, critical thinking, and

problem-solving skills needed for success in STEM fields can be enhanced by GIScience education (e.g., Gewin, 2004; Kerski, 2012; National Research Council, 2006).

## **2.6 CHAPTER SUMMARY**

Threshold concepts can be considered as conceptual gateways that, once grasped, open up a new and previously inaccessible way of thinking about the subject matter and everyday experience (Meyer & Land, 2006a). These concepts are described as being transformative, irreversible, integrative, bounded, and troublesome (Meyer & Land, 2003). Depending on student characteristics, some individuals may overcome barriers to learning and grasp threshold concepts with relative ease, while others find difficulty in doing so (Meyer & Land, 2006b). The idea of bottlenecks, places where students are likely to get stuck, was raised from the Decoding the Disciplines (DtD) methodology (Middendorf & Pace, 2004). This notion can be combined with the threshold concepts approach, concerned with how overcoming barriers to learning can help students to access particular ways of thinking and practising within a discipline (Shopkow, 2010). Thus, the troublesome and transformative criteria are widely used in the identification process of potential threshold concepts, based on the notion that troublesome knowledge indicates the existence of a threshold (e.g., Male & Baillie, 2011; Meyer & Land, 2003; Shopkow, 2010; Zander et al., 2008).

Identifying these concepts promises to enhance curriculum design and development (Cousin, 2010; Land, Cousin, Meyer, & Davies, 2007). In GIScience, the *theoretical* foundation of threshold concepts has so far been commented on based on experts' points of view, where proposed GIS threshold concepts were *interoperability*, *data models*, and *map scale* (Srivastava, 2013). Furthermore, several studies have demonstrated that there are theoretical links between GIScience and STEM disciplines in the context of shared misconceptions (e.g., Bampton, 2012), spatial thinking abilities (e.g., Lee & Bednarz, 2009), and academic and career competencies (e.g., National Research Council, 2006). Therefore, acquiring geography-related threshold concepts promises to promote students' interest and success in other STEM-related disciplines (Bampton, 2012).

## **CHAPTER 3 RESEARCH DESIGN AND METHODOLOGY**

Beginning with defining the survey population, this chapter concentrates on addressing the academic justifications of the study design and instruments. Then, this chapter addresses the study's ethical considerations, pilot testing, implementation, and administration. Further details of the quantitative and qualitative aspects of data collection and analysis are also summarized.

### **3.1 SURVEY POPULATION**

The investigation of this empirical research involved undergraduate students near the end of completing the "GEOG/PLAN 281 – Introduction to GIS" course at the University of Waterloo, Canada. The course is one of the primary introductory GIS courses at the university with many students from different major fields of study enrolled either as a pre-requisite for other geomatics courses or a completion requirement for their programs (see Appendix A for a diagram of course pathways). More importantly, this course covers a wide range of topics that are fundamental to GIScience, including data models, georeferencing, vector data analysis, raster data analysis, data sources and acquisition, data quality, and spatial data analysis and modelling. While this study's exploratory investigation is based on a single university course case study, its content is considered to be standard in terms of what would be expected in a typical introductory GIScience course. Therefore, the findings of this study are expected to be applicable to introductory GIS learners in general.

According to the GEOG/PLAN 281 course syllabus, the course provides "an introduction to digital mapping and spatial analysis using GIS software, with activities such as creating maps, analyzing geographic problems, and applying the software techniques to a variety of subject areas within geography and other disciplines." The course is structured as a weekly two-hour in-class lecture and a three-hour hands-on lab tutorial. Students first learn underlying theories and fundamental principles of GIS in the lectures and gain practical experiences of GIS software during the lab tutorials.

### **3.2 RESEARCH DESIGN**

The research design is based on quantitative and qualitative approaches, through the use of survey questionnaires and personal interviews. In general, the benefits of such instruments are that survey questionnaires can provide evidence of patterns amongst large populations, while interviews can offer more-in-depth insight into that evidence by assessing participant attitudes, thoughts, and actions (Kendall, 2008). Assessment of qualitative data was based on a phenomenographic approach. According

to Marton (1986), phenomenography is a research approach that aims to discover “the qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and various phenomena in, the world around them” (as cited in Yates, Partridge, & Bruce, 2012, p. 97). Many studies encourage adopting such an approach for threshold concepts research (e.g., Akerlind, McKenzie, & Lupton, 2011; Cope & Staehr, 2008; Cousin, 2008; Davies, 2006; Kabo & Baillie, 2009).

In Figure 3.1, the flowchart illustrates the methodological process for designing and developing the research. The first step was identifying the research goal and objectives in order to shape and define the overall scope of the study. An in-depth literature review was conducted, informing the development of the survey questionnaires and interviews. In order to conduct research with human participants, the survey instruments were submitted for research ethics review. After approval, pilot testing was then conducted to ensure clarity of questions and to identify potential areas for improvement. Any subsequent revisions to the survey also had to be submitted for and approved by the same ethics procedure. After the survey questions were approved and finalized, these instruments were implemented and administered during the data collection stage of the research. The first phase involved quantitative data collection and analysis to find evidence of patterns (e.g., concepts prone to be challenging, important factors promoting student proficiency in GIScience). Since survey data were collected over a series of academic semesters, any lessons learned were considered for further improvement. The second phase involved qualitative data collection and analysis for gaining more in-depth insight into the individual reasons and underlying driving factors for group level findings. Finally, both the quantitative and qualitative data analyses were interpreted and combined to report the research results.

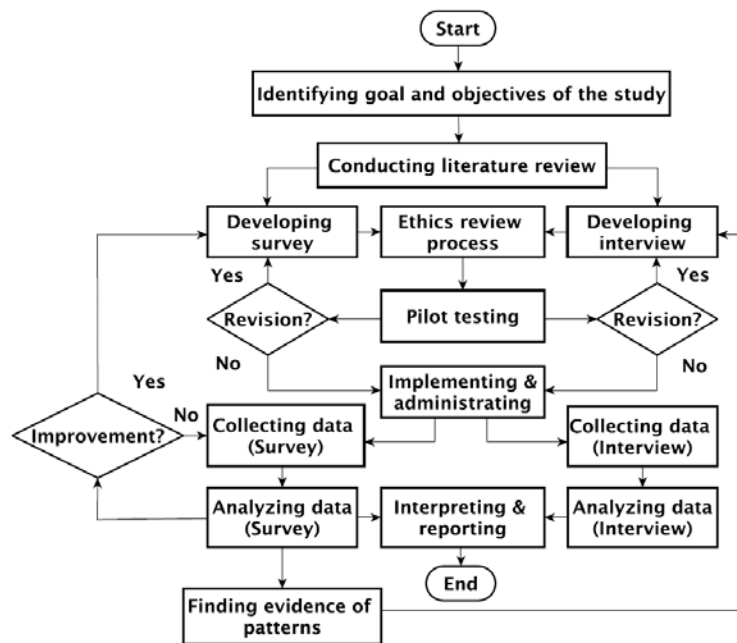


Figure 3.1 – Methodological flowchart of research.

### 3.3 DEVELOPMENT AND STRUCTURE OF STUDY INSTRUMENTS

The instruments developed for this study were semi-structured survey questionnaires and personal interviews. This section explains the rationale behind the development and structure of these instruments.

#### 3.3.1 Survey Questionnaire

The GEOG/PLAN 281 course has traditionally offered the end-of-term GIS Education User Questionnaire, first initiated as a quality assurance tool to collect student feedback about their GIS learning experiences for informing teaching. As valuable findings were gathered, this survey tool was further modified and developed for research on GIScience education (the full survey is available upon request). The survey questionnaire was designed to take about 20-30 minutes to complete. As summarized in Table 3.1, the questionnaire survey consisted of the following sections: (1) spatial thinking ability; (2) GIS knowledge areas and concepts; (3) GIS software learning for cartography and visualization; (4) GIS learning resources; (5) academic background; (6) personal background; (7) STEM education; and (8) transformative learning experience.

Table 3.1 – Description of each section in the GIS Education User Questionnaire.

Section	Name	Description
1	Spatial thinking ability	Gauging students' spatial thinking abilities
2	GIS knowledge areas and concepts	Identifying challenging GIS knowledge areas and concepts often encountered among GIScience students
3	GIS software learning for cartography and visualization	Exploring students' GIS learning experiences with the Esri's software package, ArcGIS, used in this course for their map design process and visual thinking
4	GIS learning resources	Examining students' resources used to overcome challenges involved in their GIS learning
5	Academic background	Investigating students' knowledge backgrounds and academic preparedness
6	Personal background	Investigating students' personal backgrounds
7	STEM education	Assessing students' opinions and perspectives on STEM education based on their GIS learning experiences
8	Transformative learning experience	Indicating and explaining GIS theories and concepts which, once understood, changed ways of thinking about the subject matter

### *Survey Section 1) Spatial Thinking Ability*

The first section of the survey questionnaire was structured with the Spatial Thinking Ability Test (STAT) instrument (Lee & Bednarz, 2009). With the permission of the authors, the STAT instrument was implemented in this study (i.e., added to the survey questionnaire in Fall 2014). The instrument was used to gauge the spatial thinking abilities of GIScience students. As reviewed in Section 2.5, the rationale behind this survey section was to assess students' ability levels in thinking spatially, which can be affected by their GIS learning experiences.

One reason for implementing this instrument over other available resources was that Lee and Bednarz (2009) developed it by considering the issues of existing psychometric tests in assessing spatial thinking abilities for GIScience students. Lee and Bednarz (2009) argued that these tests are limited only to psychological contexts of mental capabilities or cognitive abilities; for example, the term *spatial* used in psychometric tests typically refers to small-scale assessments (e.g., table-top) rather than the scale referring to geography (e.g., spatial patterns). Furthermore, even though some researchers attempted to overcome such limitations, the resulting instruments produced no clear consensus on measuring spatial thinking abilities at a geographic scale. The issues of reliability and validity of these instruments were also ignored or not extensively examined. The STAT instrument, on the other hand, was developed by integrating geography content knowledge and spatial thinking skills with reference to the *Teacher's Guide to Modern Geography* published by the Association of American Geographers. Moreover, this instrument incorporated spatial thinking taxonomy (Gersmehl, 2005) and other key spatial concepts identified from geography literature over the past 50 years (Golledge, 2002). Furthermore, when STAT was developed, Lee and Bednarz (2009) ensured the reliability and validity of the instrument.

The original STAT instrument consisted of eight components of spatial thinking abilities, with a total of 16 multiple-choice questions. The length of the instrument was shortened for simplicity and to reduce completion time. One question from each component was randomly obtained for the revised version (i.e., the total possible score was eight). Students' scores or answers on this instrument did not affect their course grade. The question items were as follows: (1) comprehending orientation and direction; (2) comparing map information to graphic information; (3) choosing the best location based on several spatial factors; (4) imagining a slope profile based on a topographic map; (5) correlating spatially distributed phenomena; (6) mentally visualizing 3-D images based on 2-D information; (7) overlaying and dissolving maps; and (8) comprehending geographic features represented as points, lines, or polygons (Lee & Bednarz, 2009). Sample questions are shown in Appendix B.1.

### *Survey Section 2) GIS Knowledge Areas and Concepts*

This section of the survey was designed and developed to identify challenging GIS knowledge areas and concepts, where students are likely to get “stuck” in the learning process. First, because threshold concepts are a subset of core concepts (Meyer & Land, 2006b), several studies have argued that concepts central to a discipline may be a good place to begin narrowing down potential threshold concepts (Cousin, 2006b; Davies, 2006; Zander et al., 2008). In addition, because threshold concepts are likely to be challenging (Meyer & Land, 2006a), these concepts can be further narrowed down by focusing on those core concepts that prove to be challenging (e.g., Ross, 2010). Meyer and Land (2003) also indicated that troublesome knowledge indicates the existence of a threshold. This survey section included question items, such as indicating challenging GIS knowledge areas, ranking difficulty of key concepts, and indicating the choice of examples about troublesome learning experiences (see Appendix B.2 for sample questions). Since the survey population consisted of GIScience students in GEOG/PLAN 281, the knowledge areas and concepts were prepared based on the lecture materials (see Appendix C).

### *Survey Section 3) GIS Software Learning for Cartography and Visualization*

As mentioned earlier, the GEOG/PLAN 281 course offers hands-on lab sessions for students’ practical software experiences in applying GIS theories and concepts covered in the lecture. Thus, Section 3 of the survey was designed to explore students’ GIS learning experiences with Esri’s ArcGIS software package, which is used in the course for map design and spatial analysis (see Appendix B.3 for sample questions). As reviewed earlier, some studies discussed the effect of active learning (e.g., problem-focused exercises) on students’ interest and motivation for engagement (e.g., Bain & Bass, 2012; Davies & Mangan, 2008). In a similar sense, Srivastava and Tait (2012) argued that students can be *engaged* in learning by integrating the principles and practices of GIS (e.g., converting real-world features to different GIS data); consequently, this learning process can help students to gain insight into the generalization process behind map representations. Such engagement in learning is associated with the construction of knowledge and skills through activities (Biggs & Tang, 2007; Michael, 2006; Srivastava & Tait, 2012). Bain and Bass (2012) also argued that students do not gain an understanding of threshold concepts merely by listening or learning passively.

### *Survey Section 4) GIS Learning Resources*

This section of the survey was designed to examine student resources used for overcoming challenges encountered in their GIS learning process (see Appendix B.4 for sample questions). For example, students’ different learning resources or approaches, in tolerating confusion and uncertainty,

can influence how they move through liminal spaces. First, lectures and lecture notes provide students the learning opportunity of examples and demonstrations; in addition, these resources are easily accessible for students to refresh their conceptual understanding (Reimann, 2004; Srivastava & Tait, 2010). In this respect, students who do not value lectures and lecture notes may struggle to effectively apply their theoretical understandings during the lab tutorials (i.e., a theory-practice gap may exist) (Carstensen & Bernhard, 2008; Kinchin et al., 2010; Reimann, 2004). Reimann (2004) found that the use of textbooks can sometimes act as a barrier. For example, the language and the way in which information presented in textbooks may be inaccessible for novice learners. Students' heavy reliance on peers can also hinder the process of crossing thresholds, concerned with the issues of mimicry or lack of authenticity (Alpay & Masouros, 2009; Meyer & Land, 2005; Orsini-Jones, 2008). Based on the assumption that those who acquire threshold concepts are "inside" the subject (Davies, 2006), student performance groups in GEOG/PLAN 281 were used to determine which resources were important for proficient GIS learning (i.e., exploring the learning resources valued by the higher performance groups in crossing thresholds). Performance groups were used because it is reflection of students' learning outcomes. Considering the distribution of students' performance is approximately normal (see Appendix D), the standard deviation technique was used to divide students into three performance groups for comparative analysis, as suggested and applied by Huynh (2009). This was based on the assumption that there should be reasonably small number of students (e.g., 16%) who stand out in the learning outcomes.

#### *Survey Section 5) Academic Background*

As discussed in Section 2.1.4, students' prior knowledge and experience can affect the process of acquiring threshold concepts. For example, pre-liminal variation may help to explain how a threshold concept initially comes into view, and why some students productively occupy, negotiate, and move through liminal spaces, while others find difficulty in doing so (Meyer & Land, 2006b; Orsini-Jones, 2008; Savin-Baden, 2008b). Such variation may affect students' self-confidence and feeling of knowing, which were found to be crucial in moving through liminal spaces (i.e., variation in students' grasp of threshold concepts based on individuals' preparedness or readiness) (Davies & Mangan, 2007; Efklides, 2006; Orsini-Jones, 2010; Savin-Baden, 2008b; Shanahan et al., 2008; Quinnell & Thompson, 2010). Therefore, this survey section was intended to capture student characteristics with regards to their academic backgrounds and knowledge preparedness. Questions on prior subject learning experience were structured based on key contributing disciplines to GIScience, including cartography, computer science, engineering, geography, GIS, mathematics, programming, and statistics (Fazal, 2008; Yapa, 1998). An assumption was made that students had successfully passed and achieved the learning outcomes of their indicated previous training/courses. Sample questions are shown in Appendix B.5.

### *Survey Section 6) Personal Background*

Students are also diverse in terms of their personal background, such as age, educational status, gender, and native language (see Appendix B.6 for sample questions). The rationale behind this survey section was to explore how students' different life experiences may affect the process of moving through liminal spaces. As reviewed in Section 2.1.4, Cousin (2006) argued that students may encounter or interpret threshold concepts differently depending on their emotional capital (e.g., age, gender) "because they have life experiences on which they can draw" (p. 138) in relation to their learning.

### *Survey Section 7) STEM Education*

As reviewed in Sections 2.4 and 2.5, the application of the threshold concept framework within GIScience provides valuable insight into student ability to think spatially (Slinger, 2011; Srivastava, 2013). Studies argued that such a spatial component is also critical to promoting more interest and success in other STEM-related disciplines (Baker 2012; Kerski, 2012; National Research Council, 2006; Newcombe, 2010; Sinton, 2012; Wai, Lubinski, & Benbow, 2009). This survey section was, thus, designed to examine students' attitudes, perceptions, or values towards STEM education based on their GIS learning experiences. They were examined based on several Likert items (i.e., a series of statements for a level of agreement or disagreement). Students' current interest in STEM education for pursuing their academic or career goals was also examined. In addition, students were asked to indicate their career goals and the most useful application areas of GIS. Sample questions are shown in Appendix B.7.

### *Survey Section 8) Transformative Learning Experience*

Finally, Section 8 was comprised of a single open-ended survey question that was developed and modified in the Winter 2014 academic term. According to Sproull (1988), open-ended survey responses help "to gather new information about an experience or topic, to explain or clarify quantitative findings, and to explore different dimensions of respondents' experiences" (as cited in Jackson & Trochim, 2002, p. 307). In this regard, other studies have implemented open-ended questions to explore threshold concepts and to capture various aspects of individuals' learning experiences (e.g., Davies & Mangan, 2005; Dunne, Low, & Ardington, 2003). In this study, the transformative quality of threshold concepts was assessed and examined based on student responses to the open-ended survey question. More specifically, students were asked to specify which GIS theories and concepts were difficult at first, but once understood, acted as conceptual gateways that transformed their ways of thinking about GIScience (see Appendix B.8). Students were also asked to explain how these theories and concepts

affected their ways of thinking, and indicate any previous knowledge and experience that helped during the learning process. The response rate for this question was 68%, comprising a total of 359 respondents out of 526 participants from the Winter 2014 to Winter 2015 academic terms.

### 3.3.2 Personal Interviews

Semi-structured personal interviews (see Appendix E for the guide template) were conducted with introductory GIScience students from GEOG/PLAN 281. As mentioned earlier in Section 3.2, a phenomenographic approach was adopted for the personal interviews. The rationale behind this approach is based on the notion that threshold concepts are socially constructed entities that can be encountered differently depending on individual backgrounds and experiences (Davies, 2006). Such variation suggests that “what is a threshold concept for one student may not be a threshold for another” (Ross et al., 2010, p. 47). Thus, personal interviews provide an opportunity to gain deeper insight into “how students learn or, more precisely, how individual differences may account for how and why students vary in their learning” (Meyer, 2012, p. 8). Many studies have also employed personal interviews for identifying and examining potential threshold concepts (e.g., Baillie & Johnson, 2008; Davies & Mangan, 2008; Male & Baillie, 2011; Park & Light, 2010; Taylor, 2008; Zander et al., 2008).

Based on survey questionnaire results, the interview was designed and developed to reveal how such evidence may account for students’ transformative episodes of learning in GIScience. The interview was designed to take about 20-30 minutes. As summarized in Table 3.2, the interview sections were comprised of the following: (1) critical concepts in GIScience; (2) concept-mapping exercise; (3) evidence of threshold concepts; (4) student backgrounds; and (5) GIS learning approaches.

Table 3.2 – Description of interview sections conducted with GEOG/PLAN 281 students.

Section	Name	Description
1	Critical concepts in GIScience	Narrowing down potential threshold concepts
2	Concept-mapping exercise	Arranging the selected concepts and drawing the lines between the concepts that complemented each other in learning
3	Evidence of threshold concepts	Identifying the concepts that triggered students’ transformative episodes of learning (i.e., a threshold crossing)
4	Student backgrounds	Examining the role of student backgrounds in acquiring threshold concepts and their particular ways of thinking
5	GIS learning approaches	Assessing students’ learning approaches (e.g., procedures, resources) used to learn threshold concepts

### *Interview Section 1) Critical Concepts in GIScience*

The first section of the interview began with narrowing down potential threshold concepts. For the screening strategy, red index cards of 20 bottleneck candidates (i.e., potential threshold concepts) were provided to the interview participants. These concepts, prone to be challenging among GIScience students, were identified from the survey questionnaire based on the ranking of difficulty regarding key concepts in each knowledge area. As detailed in Section 2.2, the rationale behind focusing on such bottleneck candidates was that they may represent “threshold concepts, ... clusters of threshold concepts, and ... disciplinary ways of knowing” (Shopkow, 2010, p. 327). The interview participants were asked to select all the concepts that they perceived to be critical for gaining competence in GIScience.

### *Interview Section 2) Concept-mapping Exercise*

Focusing on selected concepts from the previous step, participants were guided through an interactive concept-mapping activity, which required active participation and discussion. Such activities may provide “insights into the meaning that participants ascribe to their [learning] experiences ... [by] sorting and linking the various concepts” (Given, 2008, p. 108). As noted in Section 2.3, threshold concepts do not operate as discrete or separate entities (i.e., due to their integrative nature); thus, numerous studies have employed concept-mapping exercises to visualize, in a web-fashion, an episteme of a subject or students’ distinctive disciplinary ways of thinking (Davies, 2006; Davies & Mangan, 2005, 2007, 2008; Kinchin, 2010, 2011; Kinchin et al., 2010; Park & Light, 2010). Typically, a concept map is structured with nodes of concepts and connecting lines of links between the nodes (i.e., illustrating their relationships) (Davies & Mangan, 2007; Park & Light, 2010). Davies and Mangan (2007) suggest that such relationships can operate in one or both directions (e.g., complementing each other in learning). Thus, concept-mapping was used to explore how the difficulties of certain bottlenecks may arise from students failing to fully understand a particular threshold concept or a cluster of such concepts (Shopkow, 2010). In a similar sense, understanding threshold concepts may be dependent on the acquisition of other threshold concepts and associated building blocks (Davies & Mangan, 2007).

### *Interview Section 3) Evidence of Threshold Concepts*

After constructing a concept map, the interview focused on examining evidence of the transformative criterion of threshold concepts. First, participants were asked to circle the concepts which, once understood, changed their ways of thinking about the subject matter. This part of the interview was intended to determine which concepts acted as conceptual gateways for such transformations (i.e., a threshold crossing). These selected concepts were then further explored in the

remaining interview sections. If participants did not identify any concepts as transforming their ways of thinking, the rest of the interview then focused on exploring different aspects of student backgrounds and adopted approaches that affected their learning.

#### *Interview Section 4) Student Backgrounds*

This section of the interview was designed to explore the role that student backgrounds had on particular ways of thinking when learning threshold concepts identified in Interview Section 3. In the interview, only student background factors identified in the survey questionnaire responses as being significant for proficiency in GIScience were examined. As reviewed in Section 2.1.4.3, the rationale behind this approach was that post-liminal variation of acquiring threshold concepts may account for the “level of new conceptual understanding” (Meyer & Land, 2010, p. 63), which “may [also] involve a ‘performance element’” (Meyer & Land, 2003, p. 4). Blue index cards with additional concepts covered in the course were provided to respondents. These concepts were identified by students as potential building blocks for transformative learning (i.e., those indicated in Survey Section 8). Participants were asked to select any of these building blocks that helped to advance their understanding of their identified threshold concepts. Selected building blocks were then added to the concept-map. Blank cards were also provided to participants to write down concepts that they felt were building blocks for GIScience learning, but were not provided on the pre-labeled cards.

#### *Interview Section 5) GIS Learning Approaches*

The last section of the interview explored students’ GIS learning approaches (e.g., procedures, resources) that were helpful for acquiring a better understanding of identified threshold concepts. First, as explained in Section 2.3, software offers practical experience (e.g., learning by doing or active learning) as a means of engaging learning of conceptual materials introduced in lectures. Participants were asked how learning GIS computing software was or was not helpful for learning particular threshold concepts. Participants were provided with index cards that labelled with various learning resources and were asked to rank the cards in order of helpfulness/usefulness for learning threshold concepts. Then, based on the ranking order, participants were asked to explain how those resources were more or less helpful for overcoming barriers to learning. This part of the interview provided insight into participants’ learning approaches used to acquire threshold concepts (i.e., considering how these procedures may be modelled or applied in teaching practices). When wrapping up the interview, participants were offered an opportunity to provide additional comments regarding the identified threshold concepts or their overall GIS learning experiences.

### 3.4 RESEARCH ETHICS, PILOT TESTING, AND ADMINISTRATION

#### *Research Ethics and Considerations*

Since this research involved human participants for data collection and analysis, the study underwent the university ethics review process. This process was required to ensure participants' safety and to protect their welfare – physical, mental, and spiritual, in accordance with the *University of Waterloo Statement on Human Research, Office of Research Ethics Guidelines and Policies*, and *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans, 2<sup>nd</sup> edition (TCPS2)*. Correspondingly, this research was reviewed and received full ethics clearance through the University of Waterloo Research Ethics Committee.

Participation in this study has no known or anticipated risks (e.g., physiological, psychological, emotional, social, or economic). As suggested by the TCPS2, participation was optional or voluntary for students, “because it respects human dignity and means that individuals have chosen to participate in research according to their own values, preferences, and wishes” (Canadian Institutes of Health Research, Natural Sciences and Engineering Research Council of Canada, & Social Sciences and Humanities Research Council of Canada, 2014, p. 26). Participation in this research was optional for students, and the course instructor was not informed of who did or who did not participate in the study until after final course grades had been submitted. In addition, students' responses were not judged in terms of their academic performance or standing in the course.

Copies of the survey recruitment letter, the information-consent form, and the feedback letter are shown in Appendices F.1, F.2, and F.3, respectively. Copies of ethics documents specific to the interview are also provided in Appendices F.4, F.5, and F.6, accordingly. The recruitment process assured students' voluntary participation, since they were invited by the author who held no influential position on their participation. The research was also conducted on a “neutral” ground (i.e., any preferred locations for the survey and an empty available room for the interview) to help mitigate student pressure in declining or withdrawing from participating in the research (i.e., ensuring their voluntary participation). To allow participants to make an informed decision, full disclosure of information about the research was provided (see Appendix F). Participants were provided with a follow-up feedback letter with a statement of appreciation; in the letter, the researcher's contact information was provided for those who wished to follow-up with the research findings.

Another ethical consideration was protecting the privacy (e.g., identifiability of participants) and to ensure confidentiality (e.g., protecting information from unauthorized access, use, disclosure, modification, loss or theft) of information provided by participants. All information and data collected from this study were stored in an encrypted Excel spreadsheet and Word document on a password-protected computer database in a restricted access area of the university. All personal identifying information (e.g., name, student ID) was removed from the database, and responses were processed as anonymous. If quotations of qualitative responses were used, they were reported anonymously.

### *Pilot Testing and Administration*

A pilot study is considered to be a “small scale version or trial run in preparation for a major study” (Polit, Beck, & Hungler, 2001, p. 467). It is often used for pre-testing or trying out research instruments and procedures (Baker, 1994). For example, De Vaus (2002) suggested that pilot testing is used “to see if there are any ambiguities or if the respondents have any difficulty in responding” (p. 54). Thus, pilot testing was conducted for making necessary revisions, ensuring the proper use of research instruments and avoiding any use of misleading or inappropriate questions in obtaining information.

Pilot testing of the survey questionnaire involved 14 participants, including seven undergraduate GIScience students, four graduate students who have teaching experience in GEOG/PLAN 281, and three GIS experts from the faculty at the University of Waterloo. For the pilot testing of the interview, four graduate students who have teaching and learning experience in GEOG/PLAN 281 were recruited. Qualitative feedback and comments were used to enhance the reliability (i.e., information obtained is consistent) and validity (i.e., information obtained is appropriate) of the study instruments, such as the following:

- Ambiguous words or phrases were revised for clarity;
- Instructions difficult or confusing to follow were revised for comprehensibility;
- Redundant questions were removed or combined for simplicity and consistency;
- The process of completing the study instruments (e.g., sequence, timing) was assessed; and
- The content of the questions was assessed for their appropriateness in the measurement.

Any necessary revisions made to improve or update the survey instruments were submitted through the ethics review process once again. After revisions were completed, with the permission of the course instructor, these updated study instruments were implemented and administered for data collection from the introductory GIS course, GEOG/PLAN 281 – Introduction to GIS, at the University of Waterloo.

### 3.5 DATA COLLECTION

This section focuses on the research methodology behind the quantitative and qualitative data collection using the study instruments explained in Section 3.3. These instruments – the survey questionnaires and personal interviews – were used to collect data over a 10-day period in each academic term. The study’s assumption included that participants would truthfully and accurately answer the survey and interview questions to the best of their abilities, based on their personal learning experiences.

#### 1) Survey Questionnaire

##### *Participants*

The GIS Education User Questionnaire sequentially collected data over 10 academic terms (i.e., Winter, Spring, Fall) from Winter 2012 to Winter 2015, administered in the GEOG/PLAN 281 course at the University of Waterloo. Over this period, a total of 1,384 participated out of 1,651 enrolled students in the course, resulting in the overall response rate of 84%. Participants were comprised of multidisciplinary students from diverse academic and personal backgrounds, as reported in Section 4.2.1. Since this sample size was much greater than 30, the sampling distribution was assumed to be approximately normally distributed according to the Central Limit Theorem. Therefore, the sample size was considered to be “large enough” that the distribution of means could be assumed to follow a normal (or Gaussian) distribution (also see Appendix D), a requirement for many statistical procedures, such as parametric tests (e.g., ANOVA, t-test) concerned with differences between means.

##### *Sampling Design*

The sampling design was based on voluntary response sampling, one of the main types of non-probability (or non-random) sampling methods. As highlighted in Section 3.4, the main reason behind this voluntary sampling method was due to ethical requirements by the institution where the study was undertaken. Sampling was based on one course, which enabled consistency to be maximized in terms of participants’ exposed teaching and learning environments (e.g., available resources, coverage of subject contents, difficulty level of the course); thus, the study was able to examine variation in student learning, focusing on their characteristics with minimized external factors.

##### *Procedure of Sampling*

The GIS Education User Questionnaire was administered in GEOG/PLAN 281 as a web-based survey, which was released via the University of Waterloo’s Desire2Learn online management system. This online survey was released at the end of the term, after students had covered all lecture materials

and associated lab assignments. First, students were invited to consider participating in the study through the LEARN recruitment notice (see Appendix F.1). Those students who decided to participate were provided with an online information-consent form prior to their participation (see Appendix F.2). Since the survey was conducted online, participants were able to complete the survey questionnaire at any location with computer and internet access (i.e., their responses were submitted and collected electronically). Upon completion of the survey, a thank-you message with the researcher's contact information was displayed, as shown in Appendix F.3. This feedback/appreciation letter provided an opportunity for participants to follow-up with the research. Submitted responses were then downloaded and exported to an Excel file, and any personal identifying information (e.g., name, ID) was removed from the database. As per university ethics guidelines, these data were stored in an encrypted Excel spreadsheet on a password-protected computer in a restricted access area of the university.

## 2) Personal Interview

### *Participants*

The interview data were collected in Fall 2015 at the end of the GIS course, GEOG/PLAN 281. The response rate was 46%, comprising 30 participants out of 66 enrolled students. Even though there is no predetermined optimal sample size for personal interviews in phenomenographic research, Bruce (1997) maintained that there should be sufficient sample size to gather rich descriptions of study participants' varying conceptions about a phenomenon. Other studies (e.g., Dunkin, 2000; Josselson & Lieblich, 2003) have further argued that an optimal sample size may be obtained by *saturation*, continuing data collection until the results start to become redundant. In this regard, the sample size of the study was sufficient because there was a pattern or a form of redundancy in the meaning of interview participant responses. Nevertheless, it is important to note that there is no real saturation because each new participant can add some unique contribution to the study (Dunkin, 2000; Josselson & Lieblich, 2003).

### *Sampling Design*

As with the sampling design used for the survey questionnaire, interview data were collected based on voluntary response sampling with a similar rationale. Since personal interviews were conducted in Fall 2015, interview participants were different from those who participated in the survey questionnaire. Nevertheless, it is important to note that interview participants in phenomenographic studies are typically considered and selected based upon their *appropriateness* to the research (Yates, Partridge, & Bruce, 2012). Thus, interview participants were assumed to be appropriately sampled for

this research, since their GIS learning experiences were explored through the same GIS course as the survey participants.

### *Procedure of Sampling*

The personal interviews were conducted with participants from GEOG/PLAN 281 via face-to-face interactions. A sampling procedure similar to that described of the survey questionnaire. First, as shown in Appendix F.4, students were contacted by the interview recruitment e-mail, inviting them to consider participating in the study. Those students who chose to participate were booked with a time and location for the interview (i.e., through an online appointment booking system via youcanbook.me). When participants arrived for the interview (see Appendix G for the interview room setting and equipment), a paper copy of the information-consent form was provided prior to the research, as shown in Appendix F.5. All the participants in this study approved consent. As a data collection method, the interviews were audio-recorded and transcribed verbatim, and key notes were taken from the interviews with paper. After the interview, as shown in Appendix F.6, participants were provided with a feedback/appreciation e-mail with the researcher contact information, offering them an opportunity to follow-up with the research. The interview transcripts and the written notes did not contain any personal identifying information (e.g., name, ID). The interview transcripts were stored in an encrypted Word document on a password-protected computer in a restricted access area of the university. The written notes were also stored in the same location.

## **3.6 DATA ANALYSIS**

### 1) Quantitative Data Analysis

The key statistical methods used for quantitative data analysis were based on *descriptive statistics*, *one-way analysis of variance (ANOVA) test*, and *chi-square test for association*. The IBM Statistical Package for Social Sciences (SPSS) Statistics software was employed in this study at a 5% significance level.

### *Descriptive Statistics*

Descriptive statistics typically summarize and present the descriptive features of the quantitative data, including *distribution (e.g., frequency, percentages)*, *central tendency (e.g., mean, median, mode)*, and *dispersion (e.g., range, standard deviation)*. In terms of the distribution, the frequencies or percentages of individual values of a variable were summarized based on their specific categories. In the

study, the central tendency was also used to describe the “center” of a distribution of values, estimated by mean (or average) and mode (i.e., the most frequently occurring value in the set of data values). The dispersion, used to measure the spread of values around the central tendency, mainly dealt with the range (i.e., the difference between the highest value and the lowest value) and the standard deviation (i.e., a measure of the amount of variation in relation to the mean of a data set). For two or more categorical variables, a cross-tabulation analysis was employed to assess the frequency counts or percentages of the number of respondents in each cross-tabulated cell.

#### *Chi-square Test for Association*

The statistical significance of the cross-tabulation (or a contingency table) can be tested by using a chi-square test for association. To determine the significance, this test compares the observed frequency counts in each table cell to the counts that would be expected under the assumption of no association. This test investigates evidence of the association or relationship between the categorical variables of interest. If there was no evidence of a relationship between the variables (i.e.,  $p > .05$ ), they are considered to be independent of each other. When evidence of a relationship was found (i.e.,  $p < .05$ ), variables were interpreted as dependent on each other (i.e., associated with each other).

#### *Analysis of Variance (ANOVA) Test*

A one-way ANOVA was employed to determine whether there were statistically significant differences among the means of three or more categorical explanatory/independent variables on a dependent continuous variable (i.e., *the independent-samples t-test* was employed to serve the same purpose when the independent variables were only two categories). In the analysis, the assumption of homogeneity of variances was assessed by Levene’s test to report the appropriate  $p$ -values. If the ANOVA test indicated statistical significance, the Tukey post-hoc test (i.e., the Tukey-Kramer test for dealing with groups of unequal sample sizes) was carried out for all possible pairwise comparisons, determining which particular group differences caused the statistical significance. In the case of violation in the homogeneity of variances assumption, Welch’s ANOVA was used to test for differences between group means, and if statistically significant, the Games-Howell post-hoc test followed.

## 2) Qualitative Data Analysis

Qualitative data were obtained from the personal interviews (i.e., transcribed verbatim) and the open-ended survey question (i.e., electronically submitted responses in a written form). Key analytical methods were based on *concept-mapping analysis*, *thematic analysis*, and *Structure of Observed*

*Learning Outcomes (SOLO) taxonomy assessment.* Again, the phenomenographic approach was applied, concentrating on collective variation based on *individual* experiences (Yates et al., 2012). For example, “when statements from different students are brought together, that collective ‘pool of meaning’ reveals a rich variety in understandings” (Eckerdal, 2009, p. 30). According to Rountree and Rountree (2009), in the empirical sense, it is not possible to validate threshold concepts because what is a threshold concept for one might not be the same for another. Thus, they argued that “the best we can achieve is a sense of ‘many’ or ‘most’ learners finding a particular topic meets the requirements of a threshold” (p. 143). In this regard, the qualitative data analysis focused on identifying and examining the most prominent threshold concepts.

### *Concept-mapping Analysis*

As explained earlier, concept-mapping is “a method used to make a visual representation ... of concepts or ideas and to illustrate their relationships” (Watkins, Meiers, & Visser, 2012, p. 220). Concept-mapping can help reduce voluminous amounts of text-based data to a more manageable form (i.e., making meaningful inferences with relative ease) (Daley, 2004). The analysis relied on identifying “trends in the concept map data ... by doing *frequency counts* [emphasis added] on the prevalence of each of the code categories” (Watkins et al., 2012, p. 224). This method can be used to identify which concepts are often selected, as well as to determine where the link is likely to be made between these selected concepts (Wheeldon & Faubert, 2009).

### *Thematic Analysis*

Thematic analysis is one of the most common methods used in qualitative research (Guest, MacQueen, & Namey, 2012). Thematic analysis is defined as “a method for identifying, analysing, and reporting patterns (themes) within data” (Braun & Clarke, 2006, p. 79). This method can also “combine analysis of the frequency of codes with analysis of their meaning *in context* [emphasis in original], thus adding the advantage of the subtlety and complexity of a truly qualitative analysis” (Joffe & Yardley, 2004, p. 57). Hence, the following six stages of thematic analysis were applied (Braun & Clarke, 2006): (1) becoming familiar with the data; (2) generating initial codes; (3) searching for themes; (4) reviewing themes; (5) defining and naming themes; and (6) producing the report.

The first step involved transcribing data, reading and re-reading data, and noting any patterns or insights that emerged (e.g., the potential coding schemes). The second step was generating initial codes or categories for collating data. Based on how the study instruments were framed, these categories were

shaped by the deductive analysis procedure (i.e., a theory-driven approach specific to the conceptual foundation of the research). Excel was used to manually label student data in each row along with the columns of generated coding categories. The labelling process involved marking a numerical value of 1 under each relevant category (i.e., individual pieces of data were coded in all categories that they fit into). This coding process was conducted at the interpretative level to understand the underlying latent meaning or conceptualizations observed within the data (Joffe & Yardley, 2004). Themes were then searched through an iterative process of reading and re-reading the text data to detect the patterns of meaning “in terms of single words, themes, or concepts” (Mostyn, 1985, p. 118). For example, an individual’s response may be prompted by other participants’ responses. During the iterative process, the themes were reviewed and refined (e.g., being split, combined, or discarded); for any changes made, the coded data were updated accordingly. After no substantial change was observed, the iterative search for potential alternative explanations of the data was stopped. These solidified themes and coding categories were defined and named (see Appendix H). Last, thematic analysis was interpreted and reported, with respect to the research questions and the literature. The interpretations partially included a quantitative method, such as *counting* the frequencies of the occurrence of particular categories (e.g., the explicit words or phrases, the implicit ideas or meanings) (Guest et al., 2012; Joffe & Yardley, 2004). Where appropriate, anonymous quotations were used to report the findings, providing vivid, compelling extracted examples based on the meanings and interpretations perceived by participants (i.e., minimizing the relative weight of the author’s interpretation).

#### *SOLO Taxonomy Assessment*

The coding process of thematic analysis was conducted using the SOLO taxonomy, originally developed by Biggs and Collis (1982). The taxonomy is a widely used qualitative assessment tool to determine whether a threshold crossing has occurred (e.g., Ashwin, 2008; Lucas & Mladenovic, 2006). Hence, the taxonomy was used as a reference guide to evaluate whether students successfully acquired certain threshold concepts. According to Biggs and Collis (1982), the taxonomy is made up of the following five levels of learning outcomes, from *prestructural*, *unistructural*, *multistructural*, *relational*, to *extended abstract*, as ordered by their level of structural complexity:

- **Prestructural** – pieces of information are unconnected, with little or no organization or coherence [Verbs: misses point];
- **Unistructural** – simple connections are made between obviously related information and concepts but with no understanding of importance associated with the connection [Verbs: identify, memorize, do simple procedure];

- **Multistructural** – a number of connections might be made between different concepts and terms within the subject but with a lack of understanding of their relevance to the big picture [Verbs: classify, describe, list, combine];
- **Relational** – the parts are understood in the whole, and the student demonstrates an understanding and appreciation of the relative importance of the parts in relation to the whole [Verbs: compare/contrast, explain causes, integrate, analyze, relate, apply]; and
- **Extended abstract** – connections are made not only within the boundaries of the subject but also beyond it, and this understanding allows for generalizations to other contexts [Verbs: theorize, generalize, hypothesize, reflect, generate].

The quantitative phase of the taxonomy’s learning outcomes is made up of *prestructural*, *unistructural*, and *multistructural* levels, whereas the qualitative phase is composed of *relational* and *extended abstract* levels (Angelopoulou & Vidalis, 2014). In addition, Lucas and Mladenovic (2006) found empirical evidence that the key *qualitative* differences in the level of student understanding arose at the transitional point between the *multistructural* and the *relational* stages. The sense of appreciation of the subject area also begins to develop from the *relational* level (Angelopoulou & Vidalis, 2014; Atherton, 2013). On the other hand, students remaining in the *unistructural* or *multistructural* levels are likely to demonstrate surface level, confused understanding (i.e., often failing to recognize the significance of subject matter and to make the relations to real-world applications) (Ashwin, 2008). Therefore, the transformative quality of acquiring a threshold concept should be evident from the *relational* level, as it offers “a *qualitatively* [emphasis added] different view of the subject matter” (Meyer & Land, 2006a, p. 6). For such reasons, the coding process of thematic analysis has paid particular attention to the action verbs and descriptions related to the *relational* level (e.g., analyze, relate, apply) and the *extended abstract* level (e.g., hypothesize, reflect, generate).

In the present study, a stair-like pyramid metaphor (see Appendix I) was designed to illustrate a scenario for acquiring a threshold concept and the levels of learning outcomes in the SOLO taxonomy. This metaphor shows that those who step up stairs generally have a farther and wider view in relation to their perspectives that they were not able to see before. This illustration was made based on the notion that acquiring a threshold concept can open up “a new and previously inaccessible way of thinking” (Meyer & Land, 2003, p. 1) and provide a deeper understanding of “the subject through the integration of other concepts” (Entwistle, 2008, p. 32). On the other hand, “if the portal appears ‘bricked up’ then ... the threshold of new transformative understanding is not visible” (Land et al., p. 197). In this respect, this

illustration represents the level of competence in the subject matter in general, because crossing a threshold can progress students' level of disciplinary understanding (Meyer & Land, 2003). Therefore, structural organization of knowledge descriptions provided in the SOLO taxonomy was used to assess and evaluate whether "a student has acquired knowledge, facts, skills, concepts or problem-solving strategies" (Ashwin, 2008, p. 175), based on how they were described in students' learning-application episodes (Biggs & Collis, 1982).

### **3.7 CHAPTER SUMMARY**

The research design and methodology adopted in this study were based on both quantitative and qualitative data obtained via semi-structured survey questionnaires and personal interviews. Both study instruments were approved by the university ethics review process for conducting research with human participants. Full ethics clearance was obtained by the University of Waterloo Research Ethics Committee, and these instruments were implemented and administered in an introductory GIS course (GEOG/PLAN 281) for data collection. Participants provided consent and were recruited on the basis of voluntary response sampling. First, the survey questionnaire consisted of the eight major sections: spatial thinking ability, GIS knowledge areas and concepts, GIS software learning, GIS learning resources, academic background, personal background, STEM education, and transformative learning experience. The questionnaire was released as a web-based survey at the end of the academic term. For personal interviews, the main sections comprised of selecting critical concepts in GIScience, constructing a concept map, attesting evidence of threshold concepts, examining student backgrounds, and reviewing GIS learning approaches. At the end of the academic term, the interview was conducted with individual participants via face-to-face interactions. Quantitative data analysis methods relied on methods of *descriptive statistics*, *one-way ANOVA test*, and *chi-square test for association*. Qualitative data analysis was based on *concept-mapping analysis*, *thematic analysis*, and *SOLO taxonomy assessment*. In terms of qualitative data analysis, a phenomenographic approach was applied to investigate and examine variations in the ways that individual students experience their GIS learning.

# CHAPTER 4 RESULTS

The principal study findings are presented in this chapter. Common troublesome knowledge and threshold concepts in GIScience are identified. Then, variations in student learning journeys are assessed with respect to different liminal states. Regarding the pre-liminal state, important student background factors for proficiency in GIScience are identified. For the liminal state, the roles of important background factors, GIS software experiences, and learning resources are examined with respect to the process of learning. As to the post-liminal state, the implications of threshold concepts and proficiency in GIS learning on other STEM-related fields are discussed.

## 4.1 COMMON TROUBLESOME KNOWLEDGE AND THRESHOLD CONCEPTS IN GISCIENCE

### 4.1.1 Identifying Potential Troublesome Knowledge Areas and Threshold Concepts

In the survey questionnaire, students were asked to choose three key GIS knowledge areas that were most challenging during their learning process. As illustrated in Figure 4.1, the most troublesome GIS knowledge areas in the course curriculum were, in descending order, *spatial data analysis and modelling*, *raster data analysis*, *georeferencing*, *data sources and acquisition*, *data quality*, *vector data analysis*, and *data models* (e.g., *vector and raster*). All knowledge areas were considered when identifying all potential threshold concepts that students may have encountered in the course.

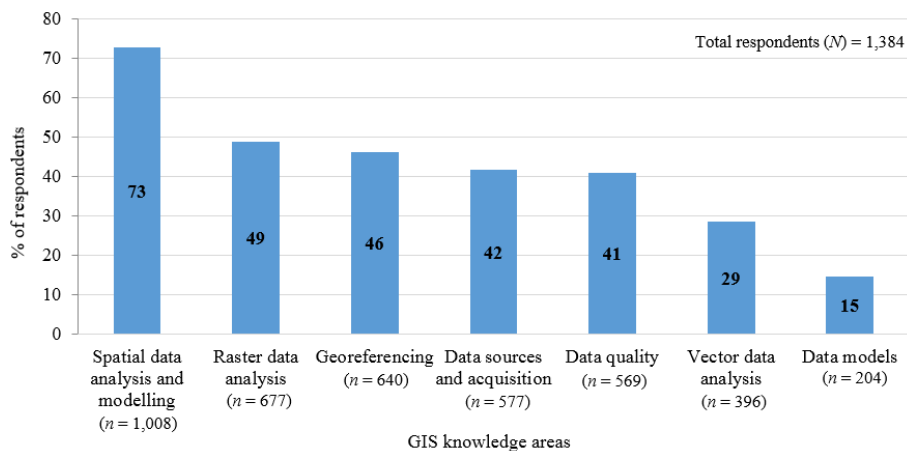


Figure 4.1 – Challenging GIS knowledge areas identified by introductory GIScience students (from Winter 2012 to Winter 2015).

Based on the knowledge areas that participants perceived as being challenging, their ranking of difficulty regarding key concepts was further examined within each area. The data of respondents who did not rank concepts appropriately (i.e., ranking all the concepts in the same order) were omitted from the analysis.

In order to identify *potential* threshold concepts (bottleneck candidates), the *troublesome* criterion was first considered, based on rankings of difficulty based on key concepts central to course materials as well as to the discipline. As explained in Section 2.1.2, these concepts, likely to be challenging, were considered to be potential indications of thresholds that may stimulate transformations in understanding (i.e., occasioned by a significant shift in the perception of a subject or a sense of being).

In this analysis, *mode* was used to identify the most frequently occurring or most common ranking order response for each concept. For knowledge areas that involved ranking of five key concepts, potential threshold concepts were selected if their mode of ranking order was either four or five (i.e., these concepts were likely to be ranked as being relatively more difficult in the knowledge area). Similarly, for the knowledge areas that involved ranking of four key concepts, potential threshold concepts were identified if their mode of ranking order was either three or four. As summarized in Figure 4.2, the ranking of difficulty regarding key concepts was illustrated for each knowledge area. Based on the mode of ranking order values, potential threshold concepts were identified.

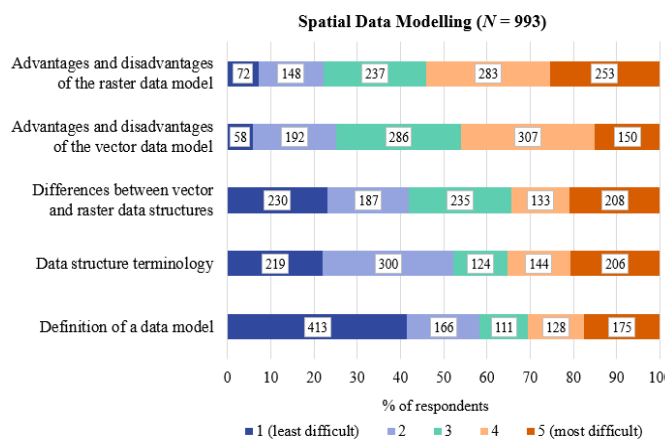


Figure 4.2.1 – Ranking the difficulty of key concepts in spatial data modelling.

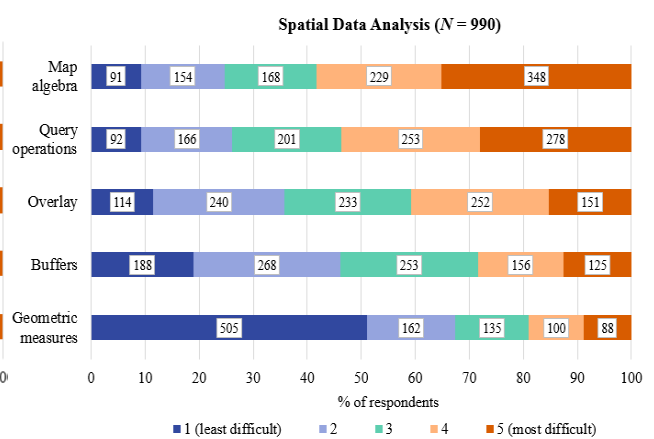


Figure 4.2.2 – Ranking the difficulty of key concepts in spatial data analysis.

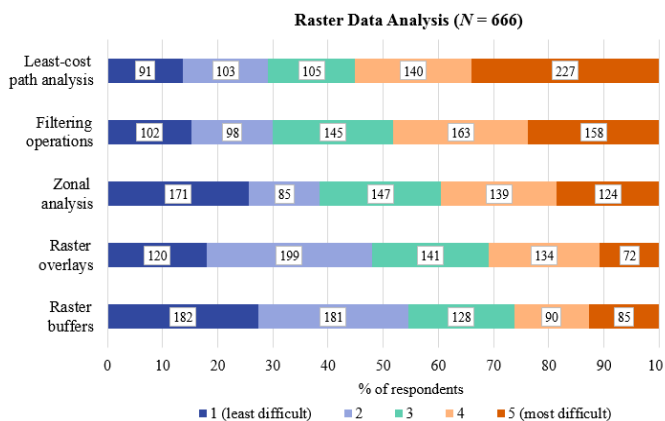


Figure 4.2.3 – Ranking the difficulty of key concepts in raster data analysis.

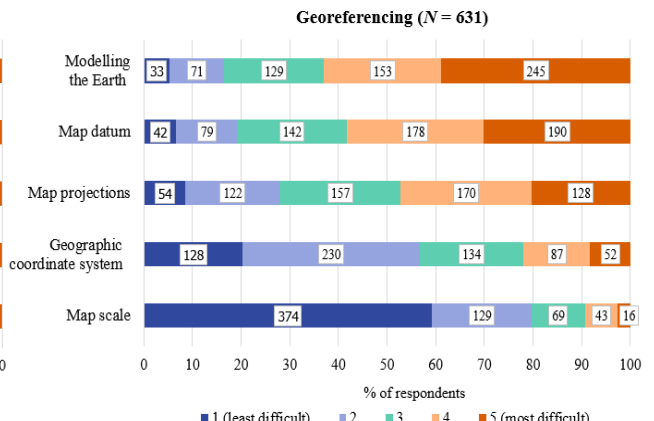


Figure 4.2.4 – Ranking the difficulty of key concepts in georeferencing.

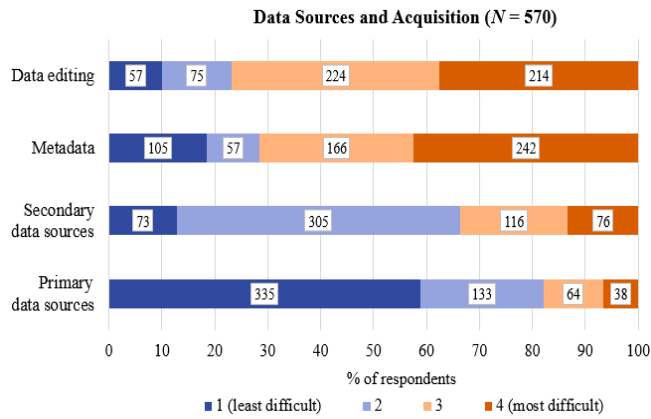


Figure 4.2.5 – Ranking the difficulty of key concepts in data sources and acquisition.

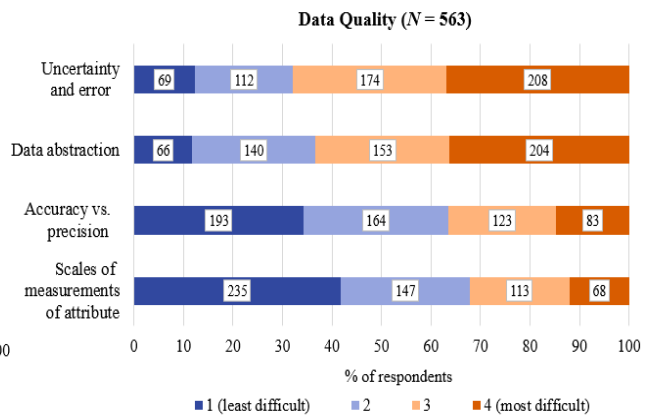


Figure 4.2.6 – Ranking the difficulty of key concepts in data quality.

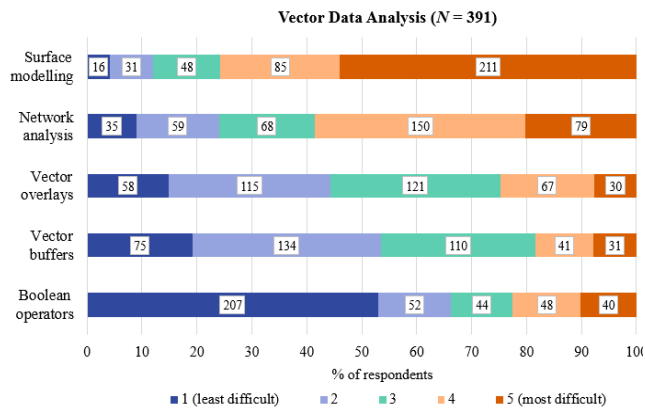


Figure 4.2.7 – Ranking the difficulty of key concepts in vector data analysis.

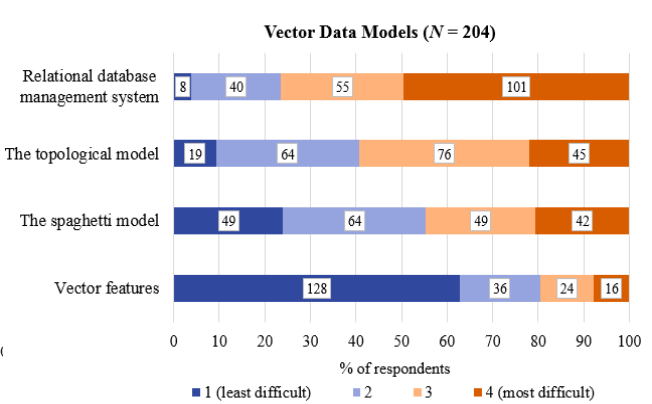


Figure 4.2.8 – Ranking the difficulty of key concepts in vector data models.

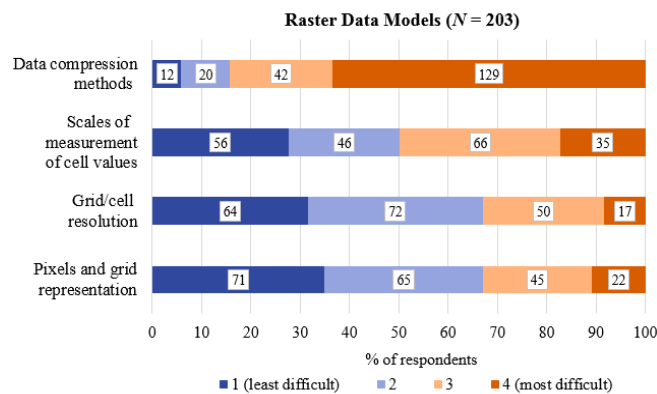


Figure 4.2.9 – Ranking the difficulty of key concepts in raster data models.

Figure 4.2 – Difficulty rankings of key concepts for each GIS knowledge area (from Winter 2012 to Winter 2015).

As summarized in Table 4.1, a total of 20 *potential* threshold concepts were identified. These concepts were used to determine which were most commonly evident in students' *transformative* episodes of learning (i.e., the key criterion in determining whether a threshold crossing had taken place, as explained in Sections 2.1.2 and 2.1.4).

Table 4.1 – Identified potential threshold concepts based on the most frequent ranking order value.

<b>Knowledge areas (Number of concepts compared in ranking)</b>	<b>Identified <i>potential</i> threshold concepts (Bottleneck candidates)</b>	<b>Most frequent ranking order value</b>
Surface data modelling (5)	Advantages and disadvantages of the raster data model	4
	Advantages and disadvantages of the vector data model	4
Spatial data analysis (5)	Map algebra	5
	Query operations	5
	Overlay	4
Raster data analysis (5)	Least-cost path analysis	5
	Filtering operations	4
Georeferencing (5)	Modelling the Earth	5
	Map datum	5
	Map projections	4
Data sources and acquisition (4)	Metadata	4
	Data editing	3
Data quality (4)	Uncertainty and error	4
	Data abstraction	4
Vector data analysis (5)	Surface modelling	5
	Network analysis	4
Vector data models (4)	Relational database management systems	4
	The topological model	3
Raster data models (4)	Data compression methods	4
	Scales of measurement of cell values	3

#### **4.1.2 Threshold Concepts Identified by GIScience Students**

Focusing on the 20 potential threshold concept candidates identified in Section 4.1.1, thematic analysis was conducted using the qualitative data collected from the open-ended survey question and the personal interview (see Appendix H for the themes and coding categories). In particular, Theme #1 (Transformative Learning Experience) and Theme #2 (Potential Threshold Concepts) were the key focus in determining the most commonly evident threshold concepts.

As noted earlier in Section 3.3.2, a threshold concept experienced by one student may not be a threshold for another due to variation in what individuals experience during the process of their learning. Therefore, based on thematic analysis of the open-ended survey question responses and the interview

transcripts, the frequency counts of the threshold concepts indicated by individual students were combined to identify the most *common* or *prominent* ones (see Table 4.2 below). For the open-ended survey question, a total of 286 participants provided descriptions of their transformative learning experiences, but 156 of them specified particular threshold concepts that triggered such transformations. During the interviews, all participants ( $N = 30$ ) selected at least one of the potential threshold concepts as being associated with their transformative learning experiences. All in all, *map projections* were found to be the most common threshold concept identified by introductory GIScience students, followed by *advantages and disadvantages of raster and vector data models*. In this study, these prominent threshold concepts were considered as exploratory examples. As further assessed in Section 4.1.3, the transformative quality of such threshold concepts were associated with student perspectives of *maps*.

Table 4.2 – Prevalence (%) of threshold concepts in students’ responses regarding their transformative learning experiences, with a 95% confidence interval (95% CI).

List of <i>potential</i> threshold concepts	Open-ended survey ( $N = 156$ )		Personal interview ( $N = 30$ )		Total ( $N = 186$ )	
	% ( $n$ )	95% CI	% ( $n$ )	95% CI	% ( $n$ )	95% CI
Map projections	32 (50)	24.73-39.37	70 (21)	53.60-86.40	38 (71)	31.19-45.15
Advantages and disadvantages of raster data model	25 (39)	18.20-31.80	43 (13)	25.60-61.07	28 (52)	21.51-34.41
Advantages and disadvantages of vector data model	23 (36)	16.47-29.69	37 (11)	19.42-53.91	25 (47)	19.02-31.51
Modelling the Earth	16 (25)	10.27-21.78	20 (6)	5.69-34.31	17 (31)	11.31-22.02
Data editing	13 (20)	7.57-18.07	27 (8)	10.84-42.49	15 (28)	9.91-20.19
Uncertainty and error	12 (18)	6.52-16.55	10 (3)	0-20.74	11 (21)	6.74-15.84
Map datum	6 (10)	2.57-10.25	13 (4)	1.17-25.50	8 (14)	3.74-11.32
Data abstraction	5 (8)	1.67-8.59	13 (4)	1.17-25.50	7 (12)	2.92-9.98
Relational database management systems	6 (9)	2.11-9.43	3 (1)	0-9.76	5 (10)	2.13-8.62
Overlay	6 (9)	2.11-9.43	3 (1)	0-9.76	5 (10)	2.13-8.62
Query operations	3 (4)	.08-5.04	17 (5)	3.33-30.0	5 (9)	1.75-7.92
Data compression methods	3 (5)	.40-6.0	3 (1)	0-9.76	3 (6)	.69-5.77
Network analysis	2 (3)	0-4.08	7 (2)	0-15.59	3 (5)	.36-5.01
Metadata	.6 (1)	0-1.89	10 (3)	0-20.74	2 (4)	.07-4.24
Map algebra	.6 (1)	0-1.89	7 (2)	0-15.59	2 (3)	0-3.42
The topological model	.6 (1)	0-1.89	7 (2)	0-15.59	2 (3)	0-3.42
Scales of measurement of cell values	.6 (1)	0-1.89	3 (1)	0-9.76	1 (2)	0-2.56
Surface modelling	0	-	3 (1)	0-9.76	1 (2)	0-2.56
Least-cost path analysis	0	-	3 (1)	0-9.76	.5 (1)	0-1.59
Filtering operations	0	-	3 (1)	0-9.76	.5 (1)	0-1.59

Note.  $N$  = the total number of participants who *specified* certain threshold concepts that transformed their ways of thinking about GIScience.

### 4.1.3 Characteristics of Threshold Concepts

As detailed in Section 3.3.2, the interviews involved a concept-mapping activity to engage participants in sharing their transformative learning experiences (see Appendix E for the instructions). This activity explored and enriched empirical evidence associated with the transformative and integrative criteria of threshold concepts (i.e., relating the threshold concepts to other GIS concepts), as well as the other characteristics of being irreversible, bounded, and troublesome. Combined with responses from the survey questionnaire and personal interviews, these characteristics were summarized and assessed with specific reference to common threshold concepts identified in Section 4.1.2, including map projections and advantages and disadvantages of *raster* and *vector* data models.

#### 4.1.3.1 Map Projections

##### *Transformative*

Map projections are defined as a system or process in which geographical locations on the curved surface of the Earth are portrayed on a flat map. This was found to be the prominent threshold concept that acted as a conceptual gateway which, once grasped, opened up a new and previously inaccessible way of thinking. The transformative quality in understanding this threshold concept was related to recognizing the importance of understanding the innate error of representing the world as a map. Quotes related to such transformative learning experiences include,

“Map projections have changed the way I look at a map. ... In previous, I did not recognize the differences of maps and the different applications. ... Map was just an accurate reflection of the real world. After this course, I tend to think about the projection and the properties of a map when I view one, or even evaluate the *quality* [emphasis added] of a map.”

“I am now more observant when I look at a map. In the past, I would look at a map and immediately accept the information that was presented, but now I look at the scene behind the map ... if its projection or generalization is appropriate. ... It is very interesting to notice how the world can be represented differently with projections in the eyes of map creators.”

“Map projections helped me view the world from a different angle. Before learning about map projections, I didn’t know what distortions were ... and how they mattered when making a map. Different projections can result in different lengths and sizes of certain locations ... stretching or compressing the real world physical features on a map. Now I understand that all projections have some level of distortion and that there is no map that’s perfect. It changed my perspective on how a map contains errors in what’s shown.”

Such transformed ways of understanding map projections also enabled students to recognize the complexity behind map-making. For example, a respondent commented that “when producing maps, I tend to pay more attention to choosing an appropriate projection. I think I’ve become more careful when I make a map. ... I realized map-making is not as simple as it seems.” In addition, such recognition of the *value* of map projections often provided students with a sense of *appreciation*: “Learning about map projections opened my eyes to a whole new world of map-making. ... Now I appreciate what goes into creating a map. ... I realized how hard it is to represent a sphere Earth on a flat surface.” Thus, understanding map projections allowed students to realize the types of work and effort involved in creating a map for visualizing geographic features. As stated earlier, the transformative episodes of learning regarding map projections act as a conceptual gateway, making students more critical about the complexity behind the map-making process and about the quality of a map behind its representation. In this regard, as explained in Sections 2.1.2 and 2.1.4, such a transformed internal view of the subject matter also relates to the troublesome nature of threshold concepts (i.e., new learning stances for being more cautious and concerned about ways of looking at a map).

### *Irreversible*

Evidence of the *irreversibility* characteristic (e.g., being unlikely to be forgotten), was also found to be associated with students’ transformative learning experiences. For example, the majority of students indicated that understanding map projections caused perspective and conceptual transformations, which would likely stay with them. This irreversibility criterion was reflected in students’ responses:

“Whenever I see a map now, I *automatically* [emphasis added] try to figure out the map projection. ... I am always critical of the projection used and am very interested in looking at how that may change the map message or promote biases. I have been in other classes where maps have been shown ... and [I] first checked if the projections used were skewing messages.”

“When I look at a map, one of the first things that I do now is figuring out what projection it is [using] because that’s so important in understanding how the map’s going to appear and if there is anything misleading in what’s displaying. ... If you get the projections wrong, it will mess up everything for map representation.”

In essence, the transformations triggered from understanding map projections were so critical for students that, from this point onward, they could no longer fail to acknowledge the importance of considering the properties of map projections and associated distortions as a means of looking at a map.

### Integrative

In the concept-mapping activity (see Appendix E for more details), participants were engaged in explaining how grasping certain potential threshold concepts transformed their ways of thinking and enhanced their understanding of other connected bottleneck candidates. They also articulated how the linked key building blocks served as foundations for their understanding of these threshold concepts. First, those participants who indicated *map projections* ( $N = 21$ ) as a threshold concept most frequently made a link with the bottleneck candidate of *map datum* (e.g., *local*, *global*) ( $n = 11$ , 95% CI [31.02, 73.74]), followed by *modelling the Earth* (e.g., *geoid*, *ellipsoid*, *topographic surfaces*) ( $n = 9$ , 95% CI [21.69, 64.02]), *data abstraction* (e.g., *classification*, *generalization*, *exaggeration*) ( $n = 5$ , 95% CI [5.59, 42.03]), *uncertainty and error* ( $n = 5$ , 95% CI [5.59, 42.03]), and *metadata* ( $n = 4$ , 95% CI [2.25, 35.84]). On the other hand, the prevalence (%) of the other connected concepts that were not within the 95% confidence interval of the most predominantly connected one, *map datum*, were not considered as relatively crucial. In a similar sense, the following building blocks were most frequently indicated as foundational to the understanding of map projections: *coordinate systems* ( $n = 15$ , 95% CI [52.11, 90.75]), *map scale* ( $n = 13$ , 95% CI [41.13, 82.68]), *geometric measures* (e.g., *distance*, *length*, *shape*, *area*) ( $n = 10$ , 95% CI [26.26, 68.98]), and *accuracy vs. precision* ( $n = 7$ , 95% CI [13.17, 53.50]). These important relationships are illustrated in Figure 4.3.

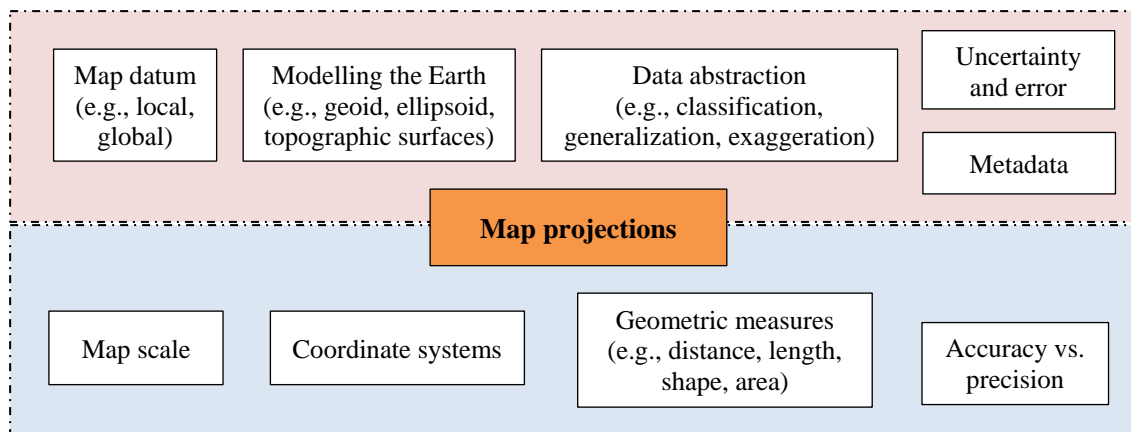


Figure 4.3 – A linkage of the threshold concept (*map projections*) with other GIS concepts (red = bottlenecks; blue = fundamental building blocks).

As pointed out in Section 2.2, bottlenecks may indicate how student difficulties may arise from failing to fully understand a threshold concept. The bottleneck candidates that were linked with map projections were in the knowledge areas of *georeferencing* (e.g., map datum, modelling the Earth), *data quality* (e.g., data abstraction, uncertainty and error), and *data sources and acquisition* (e.g., metadata). With respect to the knowledge area of *georeferencing*, where the concept of map projections was heavily dealt

with in the course, one student noted, “map datums were hard to understand before I really understood why there were many different types of projections and coordinate systems in use for modelling the Earth.” In other words, understanding the application and importance of different map projections complemented students’ understanding of map datum, which is a reference mathematical model accommodating different coordinate values used to create map projections (i.e., map projections transforming geographic to Cartesian coordinates on a flat surface based on a specific datum). Similarly, students often commented that map projections provided insight into how the properties of different distortions of size, shape, and area can be affected by the way the Earth is modelled, including geoid, ellipsoid, and mathematical calculations, as well as the topological model in terms of visualizing the arrangement of geographic features. As to the knowledge area of *data quality*, again, map projections aided students in understanding the innate error of representing the world as a map:

“By understanding the concept of map projections, I think it gave me more insight into the quality of data behind the map representation ... [because] map projections can cause errors and completely change the data you are showing to readers. ... I have better understanding of which specific types of projection is needed to minimize uncertainty and error [for the distortions].”

Furthermore, students implied that map projections helped to enhance their understanding of map abstraction, making them think about the ways of visualizing data and using different map projections for exaggeration or generalization depending on the specific needs or purposes of a map. For the knowledge area of *data sources and acquisition*, students indicated that map projections strengthened their perception of the importance of metadata (i.e., data about data), helping them understand more about the data being used in creating a map. For example, one student illustrated the integrative nature of map projections in facilitating learning about metadata as the following:

“By understanding map projections, I think it gave me more insight into the quality of data behind the map, so I started to give more *attention* [emphasis added] to metadata because it highlights the importance of the quality of data by giving you information about the projections and sources of data that we are working with. ... [For example,] it is important to know the origin of data’s map projection and which projection we need to convert to [as necessary] ... [because] it affects the way you display or organize your data in creating a map.”

Thus, recognizing the importance of map projections in the quality of map representation enabled students to value metadata more in a map-making process and to evaluate the suitability of datasets being used.

Furthermore, students often indicated that the selected key building blocks enhanced their understanding of map projections as a means of being more critical in reading maps. For example, some students remarked that map scale helped them decide which map projection to use for large (e.g., global) and small (e.g., local) scales: “map scale helped me understand map projections as a way of seeing distortions. ... It made me consider various factors that can affect what I am seeing on a map depending on the coverage area we are focusing on.” In other words, map scale helped students consider which map projection might be the most appropriate for accurately visualizing certain areas, because it can control the levels of generalization and exaggeration. As for coordinate systems, students frequently commented that they were inherently related to map projections: “Different coordinate systems specify different locations on the Earth ... [so] this concept helped me better understand why we need certain map projections and which one to choose for the specific coordinates [depending on areas of interest].” For geometric measures, the distance, length, shape, and area can get distorted or preserved by different map projections; thus, students argued that understanding the principles of such spatial concepts helped them to more accurately assess the properties of map projections, whether they were equal distance, conformal, or area:

“We learned about how distances, shapes, and areas are represented in a map and how different map projections affect one with more or less distortions. ... I realized how certain projections are more useful for displaying different parts of the world ... considering what I want to most accurately represent like distance or area. ... It made me think about which map projection to choose to minimize that [associated] distortion.”

Correspondingly, the concept of accuracy and precision also facilitated understanding of different kinds of map projections with respect to their underlying distortions and uncertainties. For example, one student noted that an understanding of accuracy and precision helped them to determine whether or not to preserve areas or angles depending on the purpose of the map. Another student also pointed out that this building block enhanced awareness of how manipulative a map can be as displayed. In this sense, map projections played an integral role in students’ understanding of other GIS concepts, as part of effectively creating a map with minimal distortions and errors.

As explained in Section 2.1.2, another *integrative* aspect of threshold concepts was also associated with exposing previously hidden interrelatedness, as a means of making sense of the ideas and procedures of a subject that did not make sense before (i.e., integration of the learners’ existing and new knowledge/experiences). One student commented, “I found map projections difficult to learn when I was in a map-making course before. I think I understood this concept better in this course because I was

already exposed to it.” Another student also noted that understanding how projections work was facilitated by previous exposure or experience to maps in a human geography course that discussed how maps could sometimes convey a biased message due to the distortions of certain map projections (i.e., Mercator projection portraying Greenland as larger than Africa).

### *Bounded*

Another evident criterion of threshold concepts was related to the *bounded* feature, typically reflected in the extension of the learners’ language use or disciplinary discourse shared within the subject community. For example, students claimed that map projections were first difficult to understand due to their discursive nature, such as terminology used specifically in the discipline: “I found that it’s hard to understand and remember all the new terms ... like the different types of map projections and their differences ... [because] previous experience has not been much help. ... I was not familiar with them.” Those students who indicated map projections as a threshold concept often commented on the extension of their language use related to the technical terms involved in the map-making process. For example, one student noted, “it felt like learning a new language. ... [So,] map projections were like a gateway ... [which] opened the doors for me to move into the areas of more technical and computer science aspects from the theoretical and human aspects of geography.” In this sense, understanding map projections helped students feel more competent in the subject community, achieved through a sense of moving into a new academic terrain or conceptual area for a privileged view of the discipline (i.e., the ways of thinking and practising distinctive to GIScience).

### *Troublesome*

In light of learning threshold concepts likely to entail *troublesome* knowledge, respondents were asked to select all statements of examples that applied to their troublesome experiences in the process of learning in GIScience. Because the nature of acquiring threshold concepts is known to advance students’ understanding of particular topics in the discipline, the troublesomeness was assessed with respect to the knowledge area covering map projections. In GEOG/PLAN 281, map projections were heavily dealt with as part of georeferencing; thus, the forms of troublesome knowledge were explored based on those who indicated this knowledge area as being difficult to learn. Out of a total of 242 respondents, 130 students indicated georeferencing as a challenging area. As reported in Table 4.3, their top three choices for forms of troublesome knowledge corresponded to exploratory examples, including *ritual knowledge*, *troublesome language*, and *conceptually difficult knowledge*.

Table 4.3 – Forms of troublesome knowledge for students who indicated georeferencing as a difficult area.

Form of troublesome knowledge	Choice of examples	% (n)	95% CI
Ritual knowledge	I knew how to create maps (or diagrams) for visual representation using these concepts, but I did not understand the logic behind them, such as the cartographic complexity involved in the representation.	54 (70)	45.28-62.42
Troublesome language	The terminology or jargon used relating to these concepts was difficult to understand, because it was not familiar to me due to disciplinary backgrounds/training or having different implications and meanings in another discipline.	47 (61)	38.34-55.50
Conceptually difficult knowledge	I struggled with these concepts, likely due to a mix of misimpressions from everyday experience, mistaken expectations, and complexity of the subject matter.	40 (52)	31.58-48.42
Inert knowledge	I understood these concepts but could not understand how they connected with the world around me or to everyday applications.	29 (37)	20.70-36.22
Tacit knowledge	These concepts were difficult because of the complexity of the knowledge that contained paradoxes, seeming inconsistencies or subtle distinctions in the meaning.	18 (23)	11.13-24.25
Alien knowledge	What was being taught about these concepts was against my perspective or fundamental point of view (e.g., ethnicity, faith).	14 (18)	7.91-19.78

*Note.* Percentages were calculated based on 130 participants who indicated the knowledge area of georeferencing as challenging (Out of a total of 242 respondents from Fall 2014 to Winter 2015).

Some students claimed that map projections were challenging to learn for several reasons. First, as to *ritual knowledge*, they pointed out the downside of just following the step-by-step lab tutorial instructions (i.e., “learning the clicks”) as a barrier to fully understanding map projections. For example, one respondent commented, “sometimes I did not understand why I was operating certain tools, I just followed instructions. ... I did not understand the purpose of my steps involved in creating maps.” In other words, even though students may have learned and know how to create maps for visual representation using a map projection, step-by-step guidance may cause them to struggle in fully understanding its operative purpose or logic behind the process of map-making (e.g., the cartographic complexity involved in the representation).

Regarding *troublesome language*, the first encounter with troublesomeness about map projections was associated with their discursive nature specific to GIScience (i.e., representing distinctive ways of thinking within the subject community). In this sense, the disciplinary discourses or terms were unfamiliar and troublesome for new entrants or novice learners of GIScience. For example, one of the respondents mentioned, “map projections were confusing because of many technical aspects of terminology behind the process from a 3-D surface [model] to a flat 2-D representation. ... I wasn’t familiar with these terminologies prior to this course.”

For *conceptually difficult knowledge*, this aspect of troublesomeness was related to the conflict with students' own intuitive beliefs and interpretations. For example, some students had misunderstood or had different expectations about the shape of the Earth (i.e., believing it to be a perfect sphere). This troublesomeness was due to the complexity of the subject matter, such as implications of the irregular shape of the Earth behind the process of map projections (i.e., the necessity for having different ones based on various mathematical models of the size and shape of the Earth):

“Theories that I learned and my own knowledge were different. ... In my knowledge, the shape of the Earth is just a perfect sphere ... like the photos show[n] around us [in our daily lives]. ... So, I was often confused by the fact that there were different map projections ... used for different models of the Earth for specific needs. ... This part was a bit time consuming to understand.”

Furthermore, another aspect of troublesomeness was related to transforming students' sense of being (e.g., learning stances). As explained earlier in Sections 2.1.2 and 2.1.4, this troublesomeness was associated with the cyclical process of learning threshold concepts. For example, because of their transformed internal view, some students indicated that such transformative episodes of learning made them more *concerned* about the complexity behind the map-making process and about the quality of map representation: “I cannot help but try to determine every time I see a map. ... It made me more *cautious* [emphasis added] about what I am seeing on the map.”

#### ***4.1.3.2 Advantages and Disadvantages of Raster and Vector Data Models***

The next common GIS threshold concepts identified by students were *advantages and disadvantages of raster and vector data models*, the spatial data model types used in GIS for representing real world features. Even though each data model type was treated separately in the concept-mapping activity, their characteristics were assessed together due to their inherent and mutually dependent relationships as well as many shared characteristics.

##### *Transformative*

As with map projections, the *transformative* nature of understanding different types of spatial data models was also related to students' ways of looking at a map, as well as to recognizing the complexity behind the map-making process:

“Before this course, I didn't know there were different types of data models. ... I thought all maps were just maps [in one simple model]. ... Learning these concepts has completely changed

the way in which I view maps. ... By understanding how maps can be created with vector and raster data, I think I've become more skilled in reading maps.”

“Understanding these different data models helped me to think about which one might be more appropriate for [working with] continuous or discrete features when creating maps ... and [this way of thinking] enabled me to appreciate the process that goes into map-making and spatial analysis. ... It helped me to see things [about a map] in a new light.”

Some students also commented about their transformed views in daily life (i.e., how real-life objects in the surrounding environment can be represented using different data models). For example, one student noted, “when I look at my GPS on my phone, which I do frequently for driving, I see the value of vector data models for navigation and transportation when travelling.” In a similar sense, another student commented, “when I see maps on the subway, I now realize that the maps are [portrayed] in vector type [such as lines and points]. ... Now I think of what type of map or what type of data model it is using.” Therefore, such transformed views were related to the integrative criterion, exposing the hidden interrelatedness of students’ existing and new knowledge and experiences. As mentioned earlier, these transformed internal views can also sometimes result in troublesomeness related to students’ new learning stances (i.e., being more cautious or critical about map-reading and about the complexity behind a map-making process).

### *Irreversible*

For the *irreversibility* criterion, respondents often commented on their new perspectives toward the conceptual understanding of spatial representation on a map: “I think that these concepts will stay with me. ... Whenever I see a map, I tend to look at what type of data model the map is using.” That is, the transformations triggered from understanding these concepts were an eye-opening event for students. From that moment, with their new learning stances, it was hard for them to disregard the advantages and disadvantages of the different data model types in spatial data modelling for mapping. As noted earlier, some key examples included students’ new value systems or learning stances established in their ways of looking at a map, as well as of thinking about how to use appropriate data models to visualize spatial features in real-world scenarios.

### *Integrative*

The *integrative* nature of threshold concepts was explored through a concept-mapping activity. First, the selected threshold concepts of *advantages and disadvantages of raster data model* ( $N = 13$ )

and *advantages and disadvantages of vector data model* ( $N = 11$ ) were most frequently connected with one another ( $n = 7$ , 95% CI [35.21, 92.06];  $n = 7$ , 95% CI [26.75, 80.95]). Both of these selected threshold concepts were often linked with other bottleneck candidates, including *data editing* ( $n = 3$ , 95% CI [.17, 45.98];  $n = 4$ , 95% CI [7.94, 64.79]), *data abstraction* (e.g., *classification, generalization, exaggeration*) ( $n = 3$ , 95% CI [.17, 45.98];  $n = 3$ , 95% CI [.95, 53.59]), and *uncertainty and error* ( $n = 2$ , 95% CI [0, 35.0];  $n = 2$ , 95% CI [0, 40.97]). For other building blocks, the predominant ones that were connected to the threshold concepts included *differences between vector and raster structures* ( $n = 11$ , 95% CI [65.0, 100.0];  $n = 9$ , 95% CI [59.03, 100.0]) and *accuracy vs. precision* ( $n = 5$ , 95% CI [12.01, 64.91];  $n = 4$ , 95% CI [7.94, 64.79]). In addition, the building block of *pixels and grid representation* ( $n = 9$ , 95% CI [44.14, 94.32]) was frequently connected with the raster data type, whereas the building block of *vector features* (*points, lines, polygons*) ( $n = 10$ , 95% CI [73.92, 100.0]) was linked with the vector data type. These key relationships are illustrated in Figure 4.4.

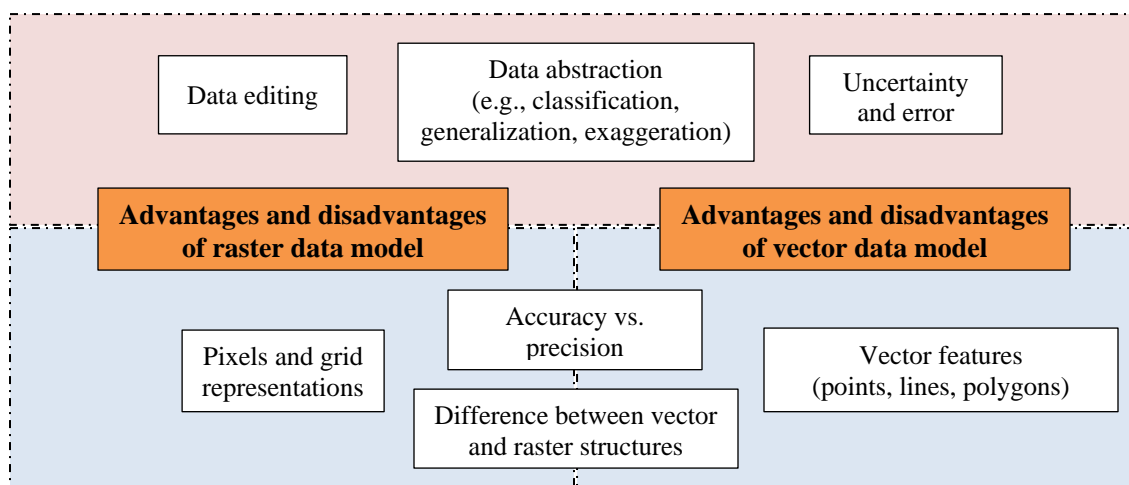


Figure 4.4 – A linkage of the threshold concepts (*advantages and disadvantages of raster and vector data models*) with other GIS concepts (red = bottlenecks; blue = fundamental building blocks).

Those bottleneck candidates that were linked with the advantages and disadvantages of raster and vector data models were in the knowledge areas of *spatial data modelling* (e.g., each type of spatial data model), *data sources and acquisition* (e.g., data editing), and *data quality* (e.g., data abstraction, uncertainty and error). For the knowledge area of *spatial data modelling*, students often commented that understanding the advantages and disadvantages of one data model type facilitated learning the other data model type. As one student commented, “one advantage of the data model type might be a disadvantage of the other one.” Students also noted that understanding different types of data models allowed them to determine whether to use raster or vector data models for a set of given mapping problems. According to one student: “I think these concepts helped me to think about the data analysis

aspects of things ... [in regard to] application sides of both of these data models. ... This GIS understanding shed more light on how maps are made.” For the knowledge area of *data sources and acquisition*, students regularly commented that understanding the advantages and disadvantages of both data-model types facilitated their understanding of data editing for database management systems (e.g., data storage, management, retrieval) in general:

“When you are editing data, you should make sure you know which ones are vector and raster because they are not the same. So, you should know their differences ... [which] helped to understand and think about what kind of data I am editing, how they are collected and manipulated, and what that data can show. ... [Now] I know that vector data models are useful for storing data that has discrete boundaries, such as country borders, land parcels, and streets. ... Raster data models are useful for storing data that vary continuously, such as elevation surface. ... [So,] understanding of the ways vector and raster data are structured helped me to think about how I could properly store and manage data to get meaningful information out of them.”

Moreover, understanding the types of data models complemented students’ learning associated with data abstraction as well as uncertainty and error in the knowledge area of *data quality*. For example, students often highlighted the importance of selecting an appropriate data model for spatial analysis and applications, involving the classification and generalization processes behind the map:

“There are different disadvantages or limitations behind each type of data model, and we need to decide which one to use for a spatial analysis. ... Understanding how the real world features can be classified and generalized helped my thought process in the creation of a map. ... I learned a lot about how to classify based on different attributes of data and [thus] how it can affect what the reader will actually pick up. ... [So, this new understanding has] changed me in that I don’t believe everything I see on the map just because it’s on the map.”

The majority of key building blocks that served as foundations for understanding the advantages and disadvantages of raster and vector data models were inherently related to these threshold concepts. For example, the building blocks of *pixels and grid representation* and *vector features (e.g., points, lines, polygons)* were the representations of the raster and vector data model types, respectively. Apparently, the building block of *difference between vector and raster structures* was also repeatedly selected as being fundamental to understanding these threshold concepts. Thus, understanding the different *structures* of each type of data model was deemed useful when learning about their advantages and disadvantages as applied to spatial data modelling and analysis:

“Vector data uses points, lines, and polygons to represent features, and raster data uses pixels [to represent real-world features], so knowing the difference between vector and raster *structures* [emphasis added] helped me to better understand the advantages and disadvantages of each vector and raster data model ... [and ultimately] to understand which type of data I need to choose for particular analysis.”

For *accuracy and precision*, students often commented on how these notions improved their thought process involved in understanding advantages and disadvantages of raster and vector data models when applied to spatial data modelling (i.e., representing real world features):

“This [building block] enhanced my understanding of the accuracy of the data models used to represent different real-life objects around me. ... [For example,] raster data model is a pixel representation system, which might not be relatively accurate and precise in terms of representations of the real world features ... because each cell only has one value. So out of the border in two cells, you can’t really differentiate how many percentages ... [are for] one cell and how much for another. ... [On the other hand,] the shapes of the vector features pretty much [accurately] represent the real world features.”

Another *integrative* aspect of these threshold concepts was also associated with exposing previously hidden interrelatedness, as indicated earlier in the examples of the transformative criterion. Similarly, one student recalled a prior experience as a useful means of the learning process in making sense of ideas: “In an urban planning course, my professor was a transport planner, and he introduced us [to] what GIS is and how useful it is in planning ... [for] different ways of modelling.” This student noted that such prior experience guided the course direction and ultimately facilitated an understanding of the different uses of each data model type in real-world scenarios.

### *Bounded*

The *bounded* feature of threshold concepts was also evident in the GIScience learning process. For example, students indicated that the advantages and disadvantages of these different data models were at first difficult to understand because they were something distinctive to the discipline: “Initially, understanding the difference between vector and raster data models was a hurdle because these concepts were the fundamental crux of a large part of the course itself ... [But,] they were not familiar to me from my background.” Students also often commented on the difficulties of understanding and remembering many different terms and characteristics specific to each data model type. As mentioned earlier, the key

features for the bounded criterion can be reflected in the extension of language use or disciplinary discourse shared within the subject community:

“These [threshold] concepts are important for *communicating* [emphasis added] data and information, particularly in map-making. I find that understanding these concepts also facilitated ... how I could present specific data and information not just in GIS, but also being selective to prepare presentation, reports, and discussions to my peers for any given scenario.”

Grasping the threshold concepts facilitated students’ understanding of the discipline-specific contexts; therefore, students may enhance their use of subject-specific language (e.g., technical terms) shared in the community of practice. Put differently, by acquiring threshold concepts, students may become more confident in *communicating* the visual information of a map to the discourse community or even to the general public.

### *Troublesome*

Since the advantages and disadvantages of raster and vector data models were covered in depth under the topic of spatial data modelling in GEOG/PLAN 281, forms of troublesome knowledge were assessed based on those who indicated this knowledge area as being difficult to learn. Out of a total of 242 respondents, 178 students indicated spatial data modelling as a challenging area to learn. Similar to georeferencing discussed earlier (see Table 4.3 for all the choice of examples on page 60), the top three forms of troublesome knowledge for spatial data modelling were found to be *ritual knowledge* (55%,  $n = 97$  out of 178 respondents, 95% CI [47.18, 61.81]), *troublesome language* (43%,  $n = 77$ , 95% CI [35.98, 50.54]), and *conceptually difficult knowledge* (42%,  $n = 74$ , 95% CI [34.33, 48.81]).

With respect to *ritual knowledge* involved in learning types of spatial data model, troublesomeness was related to simply taking the step-by-step instructions presented in the lab tutorials. Similar to understanding map projections, some students commented that they were not able to fully comprehend the purpose of the steps involved in creating maps, such as the cartographic complexity behind the representation. Due to the nature of the *introductory* course where the survey population undertook their GIS learning, some students commented on the downside of data sets being prepared and provided for their use in the lab tutorials. Thus, at least in an introductory-level GIS course, provision of pre-prepared datasets to students may potentially act as an initial barrier for students to fully engage in learning the differences between these data model types (e.g., data sources and acquisition).

For *troublesome language*, this form was relevant to the discursive nature of threshold concepts. Students often commented that the terminology used to describe different data model types was difficult to understand and remember at first, because the language used was not familiar to them (i.e., due to limited disciplinary backgrounds): “I found the wordings and terminologies a little difficult ... to understand for students who never had geography or GIS background like me.” Another student also noted, “it took a lot longer for me to understand raster data models than vector data models ... perhaps it was due to cell size and stuff like that because my prior map-making course was more focused on vector, not raster.” Students may struggle in different ways depending on their disciplinary backgrounds and familiarity with the language shared within the subject community.

Another aspect of troublesomeness was associated with *conceptually difficult knowledge* (e.g., students’ mistaken understandings or expectations). For example, some students indicated that it took a while to fully understand the difference between the different data model types, because their intuitive beliefs and interpretations differed from what they were being taught. Possibly due to the novice learners’ lack of experience, such mistaken expectations about spatial data models included their initial beliefs of “one general type of data and storage system used in mapping.” The student followed, “it was first confusing to understand how there could be different types of models used to represent the same type of data. ... I [also] thought that everything would be stored in one system [for all the data used in mapping].” Such troublesomeness may also be related to the complexity of the subject matter.

As mentioned earlier, troublesomeness was also associated with the transformative nature of threshold concepts. For example, students’ transformed internal views made them more *concerned* and *cautious* about the complexity behind the map-making process as well as the quality of map representation.

## **4.2 VARIATION IN STUDENTS’ WAYS OF THINKING AND PRACTISING**

### **4.2.1 Pre-liminal Variation: Student Background Factors for Proficiency in GIScience**

As noted in Section 2.1.4.1, pre-liminal variation depends on learners’ prior tacit knowledge, experiences, or disciplinary backgrounds. Since acquiring threshold concepts may account for enhanced disciplinary understanding, diverse student backgrounds were first assessed to identify the significant factors contributing to students’ proficiency in GIScience (i.e., a high potential to cause variations in the learning journeys). Performance grades in GEOG/PLAN 281 were available from a total of 771 participants, over the six terms from Spring 2013 to Winter 2015. The following student background factors were examined: academic preparedness, age, educational status, gender, study major, native language, type of academic background, type of geographer, and prior subject learning experience.

Table 4.4 – Average GEOG/PLAN 281 course performance according to student background factors.

Student background	Category Groups	% (n)	M (SD)	95% CI	Significance	
Academic preparedness	Not prepared	37 (286)	74.60 (9.16)	[76.88, 80.36]	*	
	Somewhat prepared	48 (366)	75.53 (9.47)	[74.56, 76.51]		
	Fully prepared	15 (119)	78.62 (9.58)	[76.88, 80.36]		
Age	18 or younger	13 (99)	74.06 (8.26)	[72.41, 75.70]	-	
	19 or 20	62 (480)	75.78 (9.17)	[74.96, 76.61]		
	21 or older	25 (192)	76.19 (10.63)	[74.68, 77.71]		
Educational status	1 <sup>st</sup> year	21 (159)	74.74 (8.72)	[73.37, 76.10]	*	
	2 <sup>nd</sup> year	57 (434)	75.49 (9.13)	[74.63, 76.35]		
	3 <sup>rd</sup> year or greater	22 (169)	77.51 (9.75)	[76.03, 78.99]		
Gender	Male	48 (373)	75.24 (9.52)	[74.28, 76.21]	-	
	Female	52 (398)	76.06 (9.39)	[75.13, 76.98]		
Major field of study	Environment and Business	33 (247)	74.42 (9.64)	[73.21, 75.63]	*	
	Aviation	6 (47)	74.52 (8.94)	[71.90, 77.15]		
	Physical geography	28 (211)	75.88 (10.46)	[74.46, 77.30]		
	Geomatics & Planning	30 (224)	76.73 (7.75)	[75.71, 77.75]		
	CS, Engineering, & Mathematics	3 (21)	80.03 (9.09)	[75.01, 76.36]		
Native language	Non-native English	39 (298)	75.64 (9.99)	[74.50, 76.78]	-	
	English	61 (473)	75.68 (9.12)	[74.86, 76.50]		
Type of academic background	Qualitative (e.g., arts, social sciences)	31 (238)	74.39 (9.99)	[73.12, 75.67]	*	
	Multidisciplinary (equally both)	48 (368)	76.02 (9.16)	[75.08, 76.96]		
	Quantitative (e.g., physical sciences)	21 (165)	76.71 (9.17)	[75.30, 78.12]		
Type of geographer	Not a geographer	42 (320)	75.05 (9.77)	[73.98, 76.13]	-	
	Human	33 (255)	75.71 (9.89)	[74.49, 76.93]		
	Physical	25 (196)	76.61 (8.25)	[75.45, 77.77]		
Prior subject learning experience	Mathematics	No	31 (238)	73.71 (9.75)	[72.46, 74.95]	*
		Yes	69 (533)	76.54 (9.20)	[75.76, 77.32]	
	GIS	No	67 (518)	75.10 (9.57)	[74.27, 75.92]	*
		Yes	33 (253)	76.82 (9.13)	[75.69, 77.95]	
	Programming	No	65 (504)	75.10 (9.64)	[74.26, 75.94]	*
		Yes	35 (267)	76.73 (9.02)	[75.64, 77.82]	
	Computer science	No	57 (443)	75.05 (9.73)	[74.14, 75.96]	*
		Yes	43 (328)	76.49 (9.02)	[75.51, 77.47]	
	Engineering	No	90 (474)	76.70 (9.35)	[75.85, 77.54]	-
		Yes	10 (51)	77.88 (11.87)	[74.55, 81.22]	
	Statistics	No	19 (147)	75.06 (8.62)	[73.65, 76.46]	-
		Yes	81 (624)	75.81 (9.64)	[75.05, 76.57]	
	Cartography	No	70 (540)	75.53 (9.42)	[74.73, 76.33]	-
		Yes	30 (231)	75.98 (9.55)	[74.74, 77.22]	
	Physical geography	No	32 (247)	75.42 (9.79)	[74.20, 76.65]	-
		Yes	68 (524)	75.78 (9.30)	[74.98, 76.58]	

Note. *n* = frequency counts. *M* = average GEOG/PLAN 281 course performance. *SD* = standard deviation. 95% CI = confidence interval. The maximum course performance is 100. \**p* < .05.

As summarized in Table 4.4, no statistical significance was found in the mean course performance difference in the following student background factors: age, gender, native language, type of geographer, and prior subject learning experiences in cartography, engineering, physical geography, and statistics. On the other hand, the following factors were identified as statistically significant for students' successful or proficient GIS learning: academic preparedness, educational status, major field of study, type of academic background, and prior subject learning experience in mathematics, GIS, programming, or computer science. Only these significant factors were examined in this study.

Regarding students' self-rated academic preparedness, 15% of students indicated that they felt fully prepared academically prior to undertaking GIS learning, whereas 37% indicated they were not prepared. The greatest proportion was 48%, who self-rated as being somewhat prepared. As expected, students who felt more prepared or had more self-confidence to undertake GIS learning achieved higher academic performance in the course than those who felt they were less or not prepared. A one-way ANOVA indicated that such mean differences between the fully prepared group ( $n = 119$ ,  $M = 78.62$ ,  $SD = 9.58$ ), somewhat prepared group ( $n = 366$ ,  $M = 75.53$ ,  $SD = 9.47$ ), and not prepared group ( $n = 286$ ,  $M = 74.60$ ,  $SD = 9.16$ ), were statistically significant,  $F(2, 768) = 7.80$ ,  $p < .001$ . Furthermore, all possible pairwise comparisons by the Tukey post-hoc test showed that, statistically, those who felt fully prepared performed significantly better than those who were somewhat ( $p = .005$ ) or not prepared ( $p < .001$ ). However, no statistical significance was found between those who assessed themselves as somewhat prepared or not prepared ( $p = .42$ ).

As for educational status, the majority of students were in their second-year of undergraduate studies (57%); the remainder included 21% first-year and 22% third-year or later students. Students' performance in the course was generally higher when their current educational status was greater. A one-way ANOVA showed that the mean differences between first-year ( $n = 159$ ,  $M = 74.74$ ,  $SD = 8.72$ ), second-year ( $n = 434$ ,  $M = 75.49$ ,  $SD = 9.13$ ), and third-year or later students ( $n = 169$ ,  $M = 77.51$ ,  $SD = 9.75$ ) were statistically significant,  $F(2, 759) = 4.24$ ,  $p = .015$ . The Tukey post-hoc test indicated that third-year or later students achieved significantly higher performance than first-year ( $p = .018$ ) or second-year students ( $p = .041$ ). However, the difference between first-year and second-year students was not statistically significant ( $p = .65$ ).

Students' major field of study was examined: "environment and business" (33% of respondents), "geomatics & planning" (30%), "physical geography" (28%), "aviation" (6%), and "computer science, engineering, & mathematics" (3%). For the category of "physical geography," the fields of study that were combined included geography, earth and environmental sciences, and environmental and resource

studies. As shown in Figure 4.5, students whose major field of study was “computer science, engineering, & mathematics” had the highest performance, followed by those in “geomatics & planning,” “physical geography,” “aviation,” and “environment and business.” The Welch’s ANOVA, employed over the standard ANOVA due to violation in the assumption of homogeneity of variances (i.e., unequal variances), revealed that those mean differences were statistically significant, Welch’s  $F(4, 109.75) = 3.40, p = .012$ . For all possible pairwise comparisons, the Games-Howell post-hoc procedure was used over the Tukey, since the homogeneity of variance assumption was not met for the standard ANOVA. The post-hoc test revealed that the mean performance difference between students in “geomatics & planning” and those in “environment and business” was statistically significant ( $p = .033$ ), and no other groups were significantly different. As approximated by unequal variance due to the low sample size in “computer science, engineering, & mathematics,” although this group had the highest performance, the mean differences to the other groups were not statistically significant.

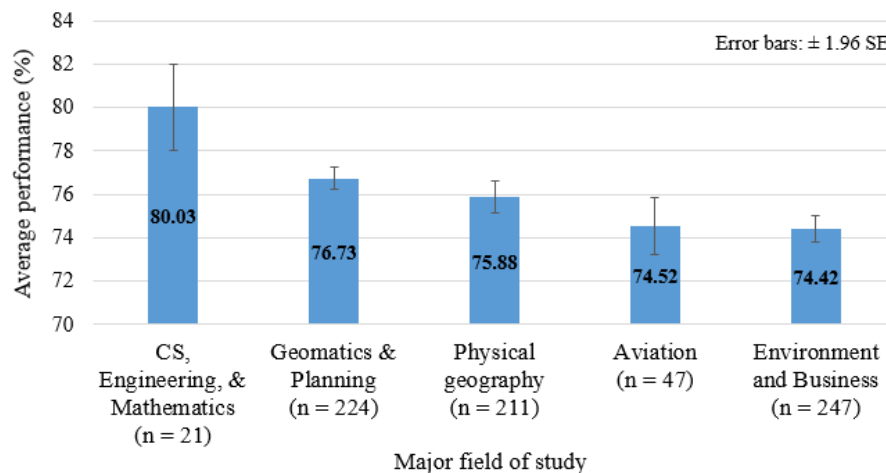


Figure 4.5 – Students’ average academic performance in the GIS course and their major field of study.

Another important student background factor was type of academic background. The majority of students (48%) indicated that they were from multidisciplinary backgrounds, followed by qualitative (31%) and quantitative (21%) backgrounds. Those from quantitative backgrounds achieved the highest course performance, followed by those from multidisciplinary and qualitative backgrounds. A one-way ANOVA indicated that the mean performance differences between the quantitative group ( $n = 165, M = 76.71, SD = 9.17$ ), multidisciplinary group ( $n = 368, M = 76.02, SD = 9.16$ ), and qualitative group ( $n = 238, M = 74.39, SD = 9.99$ ), were statistically significant,  $F(2, 768) = 3.43, p = .033$ . Furthermore, the Tukey post-hoc test showed that, statistically, students from quantitative backgrounds performed significantly better than those from qualitative backgrounds ( $p = .041$ ). No significant differences were evident in the other pairwise comparisons.

Last, the background factor found to be significant was students' prior subject learning experiences. As illustrated in Figure 4.6, students who had taken any of the following subject training/courses performed better than those who had not: mathematics, GIS, programming, computer science, engineering, statistics, cartography, and physical geography. Although all of these prior subject learning experiences were found to be helpful in GIS learning, the independent-samples t-test showed that students who had previously completed mathematics, GIS, programming, and computer science training/courses performed significantly better than those who had not:  $t(769) = 3.87, p < .001$ ;  $t(769) = 2.38, p = .017$ ;  $t(769) = 2.28, p = .023$ ; and  $t(769) = 2.09, p = .037$ , respectively.

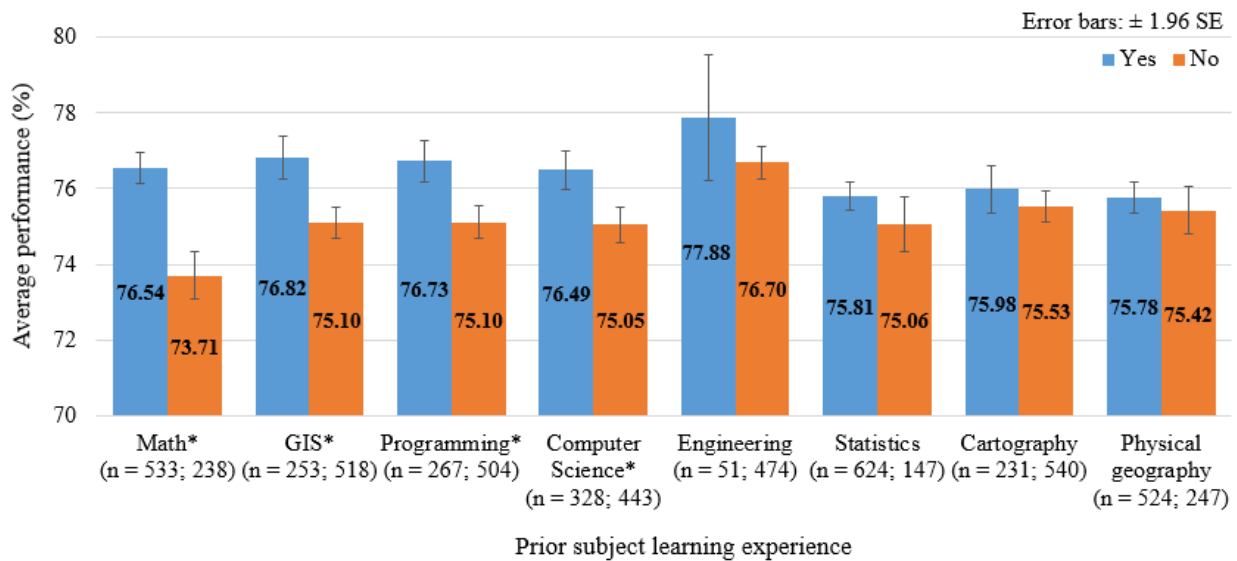


Figure 4.6 – Students' academic performance in an introductory GIS course and their prior subject learning experiences (The maximum course performance is 100; \* $p < .05$ ).

#### 4.2.2 Liminal Variation: Negotiating Liminal Spaces and Crossing Thresholds

Based on the important student background factors identified in Section 4.2.1, this sub-section assesses why some students may productively negotiate and move through liminal spaces with relative ease, while others find difficulty in doing so. In a similar sense, variations in students' learning journeys are examined based on their ArcGIS software experiences and learning approaches. Inter-seasonal variations of academic semesters are also examined by assessing differences between semester cohorts, characterized by particular groups of students (i.e., representing their perceptions or attitudes to learning).

#### 4.2.2.1 Student Background

Student background factors found to be significant for proficient GIS learning in Section 4.2.1 were assessed in relation to students' particular ways of thinking and practising in the learning process. These factors included: (1) academic preparedness; (2) educational status; (3) major field of study; (4) type of academic background; and (5) prior subject learning experience in mathematics, GIS, programming, or computer science.

##### 1) Academic Preparedness

Students' self-rated preparedness or self-confidence in undertaking GIS learning was identified as being important. This factor appeared to be associated with students' motivation or engagement in their self-regulatory process in the liminal spaces (i.e., dealing with the fear of failure and anxiety). For example, students indicated that their sense of familiarity with the subject matter from their *relevant* experiences made them feel more prepared or confident to *confront* and *deal with* confusion and uncertainty involved in the learning process. However, those who were not prepared were more likely to *retreat* or *avoid* such troublesomeness by withdrawing from further learning. Students' prior map-making and problem-solving experiences helped to facilitate engagement and confidence when approaching and dealing with similar situations of confusion and uncertainty:

“[From a prior GIS course,] I had similar map-making experiences in the assignments. ... I think those experiences made me more prepared because I knew how to *approach* [emphasis added] problem-solving [if I encounter challenges]. ... I tried to relate to my knowledge and [experiences] back to what I did in the past. ... It made me learn concepts more easily. So, I thought I was more prepared with necessary skills and experience ... [as well as] knowledge base to be successful.”

Furthermore, students' prior understanding or awareness of the useful applications of GIS was associated with their preparedness to become more readily *motivated* or *engaged* in confronting and dealing with barriers to learning in the liminal spaces:

“From planning, I already knew how useful GIS was. ... Even when lecture materials become dry with many conceptual materials, I know that I will need to use them later in the application fields in 5-10 years. So that drove me to ... make sure I know those materials ... [as well as] to understand how to operate them as a practical toolbox. [So,] that *motivated* [emphasis added] me to continue learning and working past the hard parts of the course.”

## 2) Educational Status

Another factor found to be important for proficient GIS learning was students' educational status. This background was primarily associated with the *extent* to which students had been exposed to relevant career and academic experiences in the past. First, at the University of Waterloo, co-operative (co-op) education is offered to students as an academic program, combined with professional work experience in alternating periods of study and employment (i.e., normally four months in length). Students with co-op experience acquire practical career experience, which complements their academic studies. Students with a higher educational status in the program are likely to be more exposed to such co-op or career-related opportunities, potentially making them more appreciative and conscious of real-life applications of GIS. For example, a few senior-level students commented that their co-op or real-life experiences were crucial to staying *motivated* and *engaged* throughout their learning process, likely due to their awareness about the importance of GIS in future career opportunities:

“I had a GIS-related co-op job in my second-year of study. It gave me a bit of practical experience. ... My work was helping to build a storm model [for water management] ... [using] georeferencing, and drawing and turning them into a GIS vector model assigning attributes. So I had some experience with data editing and preparing metadata. ... I could relate to more things based on my co-op experiences, and I know I can get a [similar] job [with the knowledge and understanding of these concepts]. ... I've realized how many jobs require knowledge of GIS.”

Similarly, one third-year student commented about being more attentive to job opportunities: “I *valued* [emphasis added] learning about these [threshold] concepts as they can be applied in job opportunities in the near future.” In other words, students with a higher educational status near graduation tend to be more career-focused and thus more attuned to the practical side of learning for future job opportunities.

Students with higher educational status are likely to have more prior academic experience with learning in general. For example, students in later years are more exposed to opportunities for subject learning, which may serve as foundational building blocks. As noted earlier under academic preparedness, students in later years have more experience in coping with, enduring, and tolerating obstacles or uncertainty in their learning. They may negotiate their liminal spaces by adopting similar *approaches* from the past: “The program itself was quite difficult for me at first but I soon got the hang of it. ... I knew it would just get easier by doing it a couple of [more] times.”

### 3) Major Field of Study

Students' primary fields of study was also found to be an important factor for their proficiency in GIScience. Again, these fields included "computer science, engineering, & mathematics," "geomatics & planning," "physical geography," "aviation," and "environment and business." According to all pairwise comparisons reported in Section 4.2.1, the mean course performance of GEOG/PLAN 281 was significantly higher for students coming from "geomatics & planning" than those from "environment and business" ( $p = .033$ ); No other group differences were significant.

Students majoring in geomatics and planning frequently commented about their previous exposure to relevant experiences, which aided their understanding of the subject material. For example, at the University of Waterloo, students in the geomatics and planning programs have more opportunities to learn and use tools (e.g., remote sensing, computer mapping, GIS, GPS), combined with geography and computer science aspects, in analyzing information and making meaningful decisions. Thus, these students were relatively more familiar with the subject matter of GIScience (e.g., software use, technical terminology) and were more amenable to extrapolating relevant practical applications of GIS to their major fields of study:

"In planning, I think a lot of terms or ideas are transferrable [to GIScience]. We have discussed things like slope and topology applied through GIS software ... [and] how the layouts of cities and towns may be changed depending on map projections. ... It was useful to learn how to utilize the visual and analytical power of GIS as a tool for assessment and decision-making processes. It has helped my planning interpretations to be more critical."

In other words, students in geomatics and planning had been more exposed to relevant past experiences with GIScience, facilitating motivation and engagement while in liminal spaces. On the other hand, the environment and business program focuses less on technical skills but more on the context of how businesses can be both sustainable and profitable. Thus, students in this program tended to encounter more difficulties in identifying the relevance of GIS learning to their field of study:

"The labs took a lot longer for me, and I had a hard time understanding. Other students probably found this course much more relevant to their interests and knowledge, based on their fields of study. As a business-focused student, I found only a few concepts *relevant* [emphasis added] and interesting to follow. ... [On the other hand,] I found concepts such as projections or types of data were more challenging to understand, maybe because of my [limited] background and current knowledge ... making [me perceive] this course very difficult at times."

Furthermore, this student perceived raster-related concepts as being slightly more relevant to his/her field, citing an example of studying population and income trends in particular areas of interest from a business and marketing perspective. However, compared to the fields of geomatics and planning, the environment and business program offered relatively fewer opportunities for students to apply GIS, resulting in less engagement for scaffolding their learning.

Differences in average course performance were not significant amongst other major fields of study. This consequence might be due to the multidisciplinary nature of GIS being applicable in diverse fields. For example, aviation students often highlighted the importance and relevance of GIScience to their ways of looking at a map when flying:

“A map is quite important in aviation. ... [So,] I chose map projection [as a threshold concept] because I found it relevant to my study major, aviation, in map reading. ... [For example,] map projections and distortions helped my understanding of navigation and usage of maps when it comes to flying ... giving me a better understanding of how to correctly view a map. ... Understanding the types of projections used for specific aeronautical charts gave me a better understanding of why they were used, and how the features were distorted due to the projection.”

On the other hand, physical geography students indicated that the foundational understanding of geography facilitated their GIS learning (i.e., due to its relevance in representing the Earth's geographical features on a map):

“I had geographical background and knowledge that I could relate things to. ... I think this [foundation] helped me to open my eyes how the concepts can be applied in my field. So, I was able to link with the potential and practical implications on geographical aspects. Otherwise, I don't think I would have understood their purpose or importance [in a meaningful way].”

Geography students indicated that the advantages and disadvantages of raster and vector data models were relevant in terms of understanding how physical geographical features of the Earth can be appropriately represented differently (i.e., based on data model types for spatial analysis). In a similar manner, students noted that map projections came into their *views* as something meaningful and applicable, due to their relevant experiences of encountering and dealing with maps.

As discussed later, students from the fields of computer science, engineering, or mathematics were comparably more successful in GIScience, possibly due to more relevance of fundamental skillsets, conceptual materials, and/or computer and software-related experiences. For example, one engineering

student noted that a previous working experience of dealing with data and modelling programs provided a deeper insight into the notions of uncertainty and error in GIScience (e.g., data sources and acquisition, data quality, and spatial data modelling behind map representations). In a similar sense, one computer science student claimed the following:

“The foundations of most of the contents of this course were covered in greater depth in my computer science major classes, such as projective geometry, coordinate systems and transformations, and computer graphics in general. [In this sense,] I feel that future computer science and math majors would have a relatively easy time with this class.”

Therefore, student *motivation* and *engagement* in liminal spaces were dependent on the extent to which students could *apply* and *relate* to their previous learning experiences based on their major fields of study.

#### 4) Type of Academic Background

Another important factor for proficient GIS learning was students' type of academic background (e.g., quantitative, qualitative, multidisciplinary). As reported earlier, students who self-assessed their academic background as being quantitative were significantly more proficient in GIS learning than those who self-assessed themselves to have a qualitative academic background. Students with a qualitative background frequently indicated that they struggled to understand the mathematical and programming aspects of GIS learning, particularly when dealing with data and numbers, as well as understanding the complexity behind the underlying process of mapping. In contrast, quantitative students often commented that such aspects of GIS learning were facilitated by their quantitative aptitudes, experiences, and capabilities (i.e., due to more relatable skills, experiences, and conceptual materials). One student who self-assessed him/herself as being quantitative also illustrated that this was helpful for quantitative reasoning and for understanding theoretical concepts of the subject:

“I like facts, I am a realistic person. I don't like guessing around or making general assumptions. So, I think this [way of thinking] helped me to [better] understand [different] advantages and disadvantages of vector and raster data models. It's not like it could be this or could be that. For example, a raster data model is [specific to] a type of data model, distinguished from vector.”

On the other hand, those who self-assessed as having a multidisciplinary background often indicated that their background helped them to approach problems as well as to think about the threshold concepts from two different perspectives. For example, one multidisciplinary student commented,

“The quantitative aspect of me helped to deal with data editing, while the qualitative aspect of me helped to think about the sociological implications like what I want to show to the public. So, I thought about being accurate and precise as important [in mapping] because a few meters off in a city can make a huge difference.”

Multidisciplinary students often indicated that they were able to see the operational side of data analysis and modelling in mapping, as well as the rationale behind such operations in the social context of achieving certain goals and objectives. These students claimed that their multiple different perspectives allowed them to *relate* to a wider range of applications. For example, one of the students mentioned, “I was more open-minded to look[ing] at things ... [that allowed me to have] more meaningful understanding of them ... [because] it was easier for me to relate in different perspectives, instead of with just one view.”

#### 5) Prior Subject Learning Experience (Math, GIS, Programming, or Computer Science)

Students’ prior subject learning experiences in mathematics, GIS, programming, or computer science were found to be highly important for proficiency in GIScience.

##### *Mathematics*

Students acquired prior mathematics learning mainly through previous calculus and algebra-related training/courses. They commented that such experiences facilitated and engaged them in thinking about how mathematical functions can be related and applied to the operational processes of GIS mapping. For example, one mathematics student noted, “math covered many quantitative conceptual materials, so working with quantitative data in GIS was helpful ... [to understanding] how mathematical functions can be applied for a spatial analysis.” Students identified GIScience concepts, including coordinate systems, map scale, data abstraction (e.g., generalization), and map algebra, as being highly related to their prior learning in mathematics.

In relation to coordinate systems, some students commented that their prior math learning experiences were helpful in dealing with numerical values, such as coordinate format conversion (i.e., understanding how the degrees/minutes/seconds format works with respect to the decimal degrees format on longitude and latitude). Similarly, students noted that their prior math learning about geometry and trigonometry aided their understanding of measuring angles/directions (e.g., bearing), distances, and areas of locations dependent on the spatial reference of coordinate systems.

Regarding map scale, students indicated that distance unit conversions applied when calculating geometric measures of locations (i.e., measuring the relationship between distances/areas on a map and corresponding distances/areas in the real world) were facilitated by prior learning of mathematical concepts. Students with mathematics backgrounds may be more prepared and amenable to understanding the degree of generalization (e.g., simplification of spatial features) of real-world objects controlled by map scale.

Furthermore, mathematical operations of GIS in mapping were associated with spatial data modelling and analysis. In particular, students indicated that raster-type data analysis, such as map algebra, was facilitated by prior math knowledge and experiences (i.e., general calculations for multiplications and conversions). According to one student, “Calculus helped me to learn about map algebra because I know how to deal with numbers and mathematical calculations.” For spatial data modelling and analysis, students commented that math-like operational expressions were easier for them to understand, including *arithmetic* (e.g., addition, subtraction, multiplication, division), *Boolean* (e.g., AND, NOT, OR, XOR), and *relational* (e.g., <, <=, <>, =, >, >=) operators.

### *GIS*

Students with prior GIS learning indicated that these experiences were mostly obtained from other introductory-level courses at the undergraduate level (e.g., GEOG 181 – Principles of GIScience, GEOG 187 – Problem Solving in Geomatics). As expected, students indicated that previous exposure to the subject matter provided them with more foundational knowledge and preparedness, facilitating their overall GIS learning process in GEOG/PLAN 281. These students indicated that prior understanding of the history of mapping, gained from previous courses/training, was helpful for recognizing relationships and becoming engaged in their GIS learning. For example, students noted that such understanding helped them recognize the *value* of map-making: “We learned about the history of map-making ... [for] what we know now as GIS today. I found that was extremely important in creating the basis of my GIS learning ... [which made me] *value* [emphasis added] what I was doing.” Thus, such a value system established from previous GIS learning experiences may help students to be better engaged with learning, and as a result, be in a better position to productively negotiate their liminal spaces with relative ease.

As noted earlier, the integrative nature of a threshold concept was associated with exposing previously hidden interrelatedness. Students commented that their previous exposure to learning about map projections helped them to perceive and understand this concept more easily when encountered again.

One student noted that “I had better understanding of map projections in this course, thanks to my previous GIS learning. ... It was first difficult and complicated [from that learning] but became a lot easier because I had already been exposed to them.” In other words, the idea of map projections from previous GIS learning became more clear or made sense with relative ease, because students had already encountered and dealt with the associated difficulty of learning in the past. On the other hand, although relevant previous knowledge can help student learning, some students indicated that they did not have a transformative learning experience in GEOG/PLAN 281 because the subject matter was already quite familiar for them (i.e., they had already acquired a threshold concept and had the associated transformations from previous GIS learning). For example, one student noted, “[this course] hasn’t transformed me in any significant way. I think I was [already] familiar with a lot of the topics covered from previous [GIS] learning.”

In addition, students commented that their relevant map-making experiences in previous GIS course/training made them feel more confident and competent in using the software in the course (i.e., for applying the theories and concepts). One student commented, “I was familiar with working with the GIS software for mapping. ... It made me learn and grasp the concepts more easily ... [because] I was able to apply more to the software [with relative ease].”

### *Programming*

Students who had prior programming experience had gained this knowledge from previous computer science-related training/courses. A few students indicated that GIScience concepts were facilitated by their previous programming experience, including database management systems, query operations, and Boolean operators (e.g., AND, NOT, OR, XOR). Students commented that these GIScience concepts were widely used in programming. For example, one student noted, “prior programming experiences were helpful for [understanding] Python [languages used for GIS automation lab exercises] and query operations ... such as ‘Equal to’ and all that because I knew what this was doing. The language itself was not very complicated.” Thus, previous experience with operating such commands in programming helped students to more easily understand query operations used in GIScience for selectively displaying and retrieving information from a database.

Students’ knowledge and competence in programming made them more receptive to understanding how certain operations can be carried out in the ArcGIS software (e.g., Python coding embedded in a GIS environment). This competency was associated with students’ understanding of programming language rules (i.e., a syntax). Since a small error in syntax can cause a program to function incorrectly, students

indicated that their prior programming learning experiences were helpful for debugging and troubleshooting syntax errors behind the operations. Out of a total of 267 respondents with prior programming experience, the key languages they learned included Java ( $n = 112$ , 42%), Python ( $n = 91$ , 34%), C ( $n = 55$ , 21%), HTML ( $n = 54$ , 20%), C++ ( $n = 53$ , 20%), and Visual Basic ( $n = 32$ , 12%).

### *Computer Science*

Students commented that prior learning experience in computer science helped them to understand the internal functions of GIS and their use of technical terminology. Students indicated that a computer science background facilitated their learning of certain GIS-related concepts and skills, such as spatial data models, database management systems, map projections, and coordinate systems and transformations. For example, a few students noted that their prior understanding of computer graphics helped them to more easily understand the raster data model used in map representation (i.e., an array of pixels arranged in rows and columns on a computer screen): “Raster concepts are not too difficult to understand if you have knowledge of how computer monitors work.” Similarly, some students noted that familiarity with 3-D projections (i.e., a method used for displaying 3-D points to a 2-D plane) from a computer graphics course facilitated their understanding of map projections in GIScience. However, students without prior computer science knowledge and experience often indicated that they encountered difficulties with the same concepts, such as raster and vector data models (e.g., the efficiency of different methods of data storage) and data types (e.g., floats, double, integer). One student with prior computer science learning noted, “the importance of efficiency and optimization [in computer science] ... [was similar to GIScience in terms of] different ways to store information ... [because] not all of them are as useful as the other ones. Some sacrifice convenience for efficiency, and vice versa.” Clearly, students negotiate and move through the liminal spaces differently, depending on their prior subject knowledge and experience.

#### **4.2.2.2 GIS Software Learning (ArcGIS)**

Another characteristic examined in this study was students’ experience with learning GIS software. As noted earlier (Sections 3.1 and 3.3.1), the GEOG/PLAN 281 course employs Esri’s ArcGIS software package in hands-on lab tutorials. In the survey questionnaire, students were asked to rate the difficulty of learning the ArcGIS software based on a scale of 1 (easy) to 5 (difficult); then, they were grouped into the categories of “easy/somewhat” (i.e., a rating of 1 or 2), “neutral” (i.e., a rating of 3), and “difficult/somewhat” (i.e., a rating of 4 or 5). In summary, most students (47%) rated the GIS software as neither difficult nor easy (i.e., in the category of “neutral”), but 33% of students found it

relatively difficult to learn and only 20% found it to be rather easy. As expected, students who found the software easier to learn performed better in the course. A one-way ANOVA indicated that the mean course performance difference between those who found the GIS software “easy/somewhat” ( $n = 153$ ,  $M = 76.89$ ,  $SD = 9.63$ ), “neutral” ( $n = 365$ ,  $M = 76.34$ ,  $SD = 9.03$ ), and “difficult/somewhat” ( $n = 253$ ,  $M = 73.95$ ,  $SD = 9.75$ ) was statistically significant,  $F(2, 768) = 6.46$ ,  $p = .002$ . The Tukey post-hoc test showed that students who found the GIS software to be relatively difficult to learn tended to perform significantly lower than those who found it to be relatively easy ( $p = .006$ ) and neutral ( $p = .006$ ). On the other hand, the difference between those who rated it as “easy/somewhat” and those who rated it as “neutral” was not significant ( $p = .81$ ). Therefore, students who rated the difficulty of ArcGIS software to be “easy/somewhat” or “neutral” were considered to be similar, while those who rated the software as “difficult/somewhat” were considered as a separate group.

In the survey questionnaire, students were asked to indicate whether hands-on lab assignments were constructive towards their overall learning process in GIScience. Out of a total of 1,384 participants, 82% ( $n = 1,140$ ) indicated that hands-on lab assignments helped them better understand relevant GIS theories and concepts, while 13% ( $n = 181$ ) indicated that hands-on lab assignments were not helpful or impeded their learning. The remaining 5% ( $n = 63$ ) indicated that they had no opinion. A chi-square test showed evidence of a relationship between students’ difficulty with the ArcGIS software and their hands-on lab assignment experiences as a constructive means of learning,  $X^2(1) = 27.05$ ,  $p < .001$ . For example, out of students who rated ArcGIS software learning as “easy/somewhat” or “neutral,” 69% ( $n = 785$ ) agreed that the lab assignments fostered their understanding of GIS theories and concepts, while there was only 31% ( $n = 355$ ) agreement among those who rated ArcGIS as “difficult/somewhat.” In other words, students who found the software relatively easy to learn were able to better engage in the hands-on lab assignments designed to build their comprehension of GIS theories and concepts.

Engagement and experiential learning through the use of GIS software packages was found to be an important factor in the process of learning threshold concepts. For example, students who indicated that the software was difficult to learn described their experiences with characteristics that are typical of liminal spaces (e.g., time-consuming, emotional reactions). One student commented, “I felt a *darkness* [emphasis added] about the assignments and course materials. I found that I was putting a lot of time into each assignment. ... ArcGIS can be intimidating, challenging, and frustrating at times.” In particular, students often commented about the difficulty of the software in terms of its trial and error process involved in learning:

“Hands-on lab assignments were a constant stressor because most of the time I was stuck in the

middle of the lab not knowing how to move ahead. ... I got quickly frustrated when errors came up. I couldn't understand what they meant because we were never taught about the jargon used in that error message. ... The difficulty was finding out what I did wrong and re-running [the steps] many times until I figured it out. It was very time consuming and frustrating.”

Thus, students who found the software difficult to learn often struggled with troubleshooting syntax errors behind the operations. On the other hand, those who found the software easy to learn productively dealt with such troublesomeness in a different manner: “When there was an error, it showed why it did not go through. It was easier for me to understand [that error] and to track down the use of previous tools. ... I soon got the hang of it.” Such competency helped students withstand and tolerate confusion and uncertainty involved in their software learning. Notably, competent GIS software users were able to negotiate and move through liminal spaces with relative ease. They were more likely to benefit from the applications of GIS software, while also reinforcing conceptual materials that were covered in lectures.

Students frequently commented about their enhanced understanding of map projections through the practical use of ArcGIS during the lab tutorials (i.e., via the visual display of geographic information and communication of geospatial analysis). This facilitated learning was also associated with effective problem-solving experiences through hands-on lab tutorials:

“One of the most difficult concepts to understand was the use of different map projections. ... I think it was a tricky concept to understand abstractly. ... After much practice in the lab, I was able to better differentiate between them and their use ... [because] the practical use of the software helped me to display and visualize the outcomes of how the concepts work depending on how I use them. ... I can [visually] see the differences with my eyes on the screen ... [and] explain why I am doing such things in the problem-solving process. ... [These experiences] presented an opportunity to apply the conceptual materials being taught in the lecture.”

Thus, students' experience with GIS software can engage them in grasping why certain projections should be used over others for visualization, depending on an areas of interest. This engagement ultimately provides students with a deeper understanding of the processes behind map-making and spatial analysis.

In addition, the *visual layout* and *language* (e.g., use of technical terminology) aspects of ArcGIS software learning were assessed. According to a chi-square test, student difficulty ratings of ArcGIS were found to be dependent on whether they indicated its visual layout and language aspects of learning

as a barrier,  $X^2(2) = 36.06, p < .001$  and  $X^2(2) = 77.79, p < .001$ , respectively. It was evident that both of these aspects affected students' process of learning and acquiring software skills. As for visual layout, 7% of students who rated ArcGIS software learning as "difficult/somewhat" found the visual layout of ArcGIS to be a significant barrier to their software learning. On the other hand, only 2% of those who rated ArcGIS as "easy/somewhat" or "neutral" found visual layout to be troublesome.

The difference between these groups was even greater when considering the language aspect of ArcGIS learning. For example, 18% of students who rated ArcGIS as "difficult/somewhat" identified use of technical terminology as a barrier, while this was only 6% for those who rated ArcGIS as "easy/somewhat" or "neutral." Therefore, the visual layout of ArcGIS was considered to be relatively user-friendly and generally facilitated the software learning process, while language/terminology was deemed to be a significant barrier to learning. One student commented, "many operations in the ArcToolbox were confusing when [I was] reading the description ... due to the [unfamiliar] terms not discussed in class. This often led to frustration and back tracking." Similarly, some students struggled with understanding the jargon or technical terminology appearing in ArcGIS messages for troubleshooting syntax errors behind the operations.

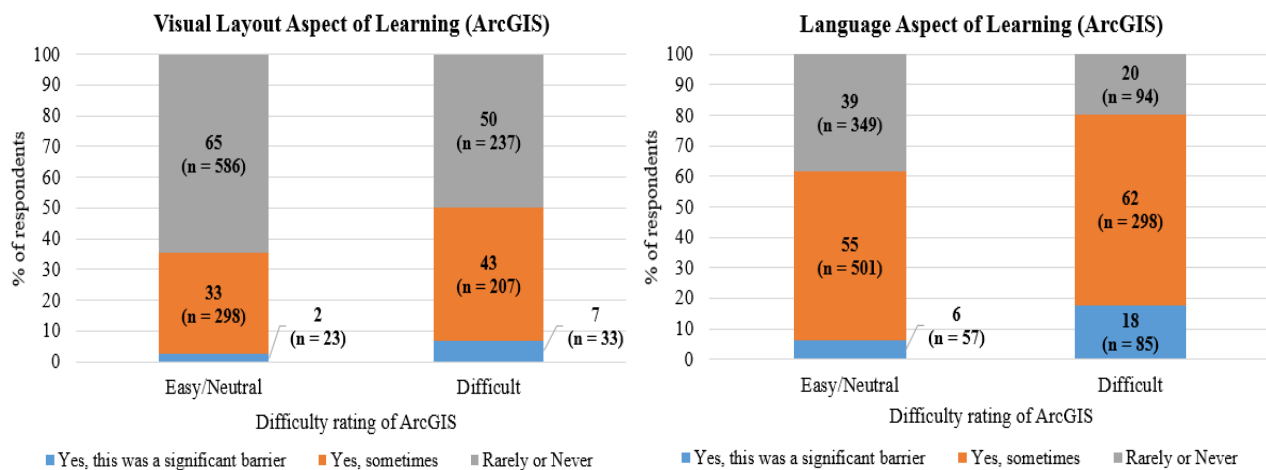


Figure 4.7 – The difficulty rating of learning ArcGIS and its visual layout (left) and language (right) aspects of learning as a barrier.

#### 4.2.2.3 GIS Learning Resources

Learning resources were also examined in terms of what resources students found helpful during the process of learning threshold concepts. In GEOG/PLAN 281, the following resources were available to assist students with GIS learning: lectures and lecture notes, tutorial instructions/sheets, online resources (e.g., ArcGIS Help, websites), library resources (e.g., books), discussion with peers, and

discussion with instructors (e.g., faculty, TAs). In the survey questionnaire, students were asked to rank these resources in order from the least helpful to the most helpful, as summarized in Figure 4.8. Overall, based on the average helpfulness ranking score, the learning resources valued by GIScience students were prioritized in the following order: online resources ( $n = 1,352$ ,  $M = 4.13$ ,  $SD = 1.43$ ), discussion with peers ( $n = 1,353$ ,  $M = 4.12$ ,  $SD = 1.49$ ), lectures and lecture notes ( $n = 1,353$ ,  $M = 3.90$ ,  $SD = 1.60$ ), discussion with instructors ( $n = 1,353$ ,  $M = 3.70$ ,  $SD = 1.55$ ), tutorial instructions/sheets ( $n = 1,352$ ,  $M = 3.50$ ,  $SD = 1.61$ ), and library resources ( $n = 1,352$ ,  $M = 1.65$ ,  $SD = 1.13$ ).

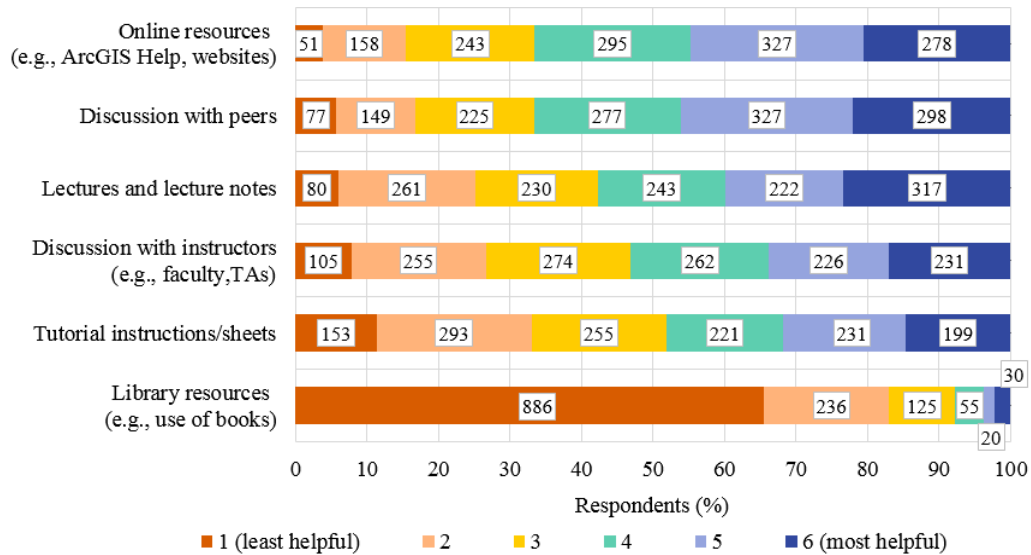


Figure 4.8 – Ranking of helpfulness regarding resources available for GIS learning (from Winter 2012 to Winter 2015).

As noted earlier in Section 3.3.1, student performance groups were further examined to compare and identify which learning resources were more helpful for gaining proficiency in GIS learning. As previously mentioned, the standard deviation technique was applied to categorize students into a high-performance group, intermediate group, and low-performance group. Based on the GEOG/PLAN 281 course grades for 771 students from Spring 2013 to Winter 2015 academic terms, the overall performance average was 75.66%, and the standard deviation was 9.46. The high- and low-performance groups included students with an overall course performance greater or lower than one standard deviation above or below the mean (i.e., greater than 85.12% or lower than 66.20%), respectively. The intermediate group included students with a performance between 66.20% and 85.12%. In summary, 15% of students ( $n = 118$ ) were categorized in the high-performance group, 71% ( $n = 546$ ) were in the intermediate group, and 14% ( $n = 109$ ) were in the low-performance group. Based on these groupings, average ranking scores of helpfulness for the six types of learning resources were compared, as illustrated in Figure 4.9.

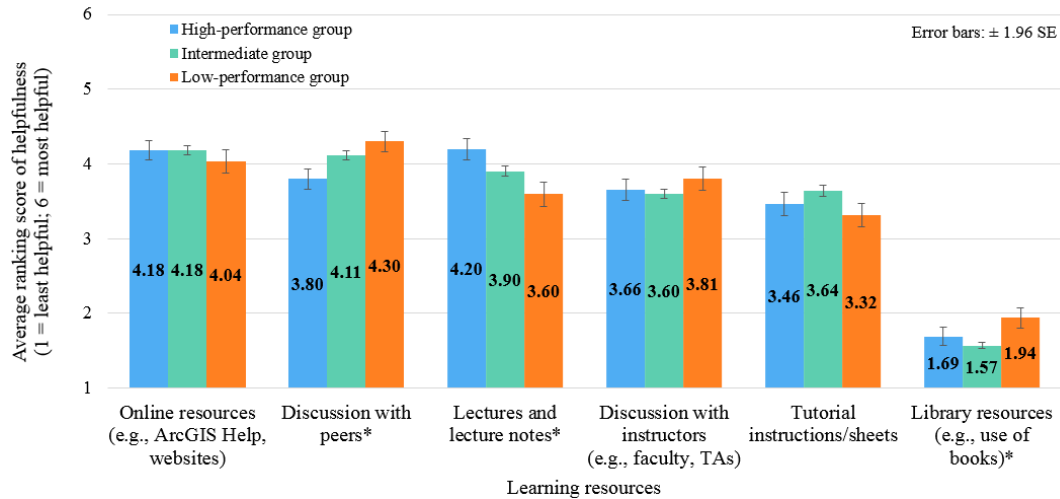


Figure 4.9 – Average ranking score of helpfulness for learning resources by performance groups (\* $p < .05$ ).

According to a one-way ANOVA, the difference between average ranking score of helpfulness by the performance groups was significant for the following resources: “discussion with peers,”  $F(2, 746) = 3.39, p = .034$ ; “lectures and lecture notes,”  $F(2, 746) = 4.01, p = .019$ ; and “library resources,”  $F(2, 745) = 4.56, p = .011$ . As for discussion with peers, the Tukey post-hoc test revealed a statistically significant difference between the high-performance group ( $n = 114, M = 3.80, SD = 1.49$ ) and low-performance group ( $n = 104, M = 4.30, SD = 1.43$ ),  $p = .031$ , but no other group differences were significant. Therefore, although the majority of students valued peer discussions as a helpful learning method, this learning approach was especially valued by the low-performance group. These students were more likely to turn to their classmates and peers for help, since they likely could not grasp threshold concepts or overcome knowledge barriers to complete an assignment independently. Similarly, the Tukey post-hoc test showed that lectures and lecture notes were significantly more valued by the high-performance group ( $n = 114, M = 4.20, SD = 1.51$ ) than the low-performance group ( $n = 104, M = 3.60, SD = 1.66$ ),  $p = .013$ . Regarding library resources, the Tukey-post-hoc test revealed a statistically significant difference between the intermediate group ( $n = 530, M = 1.57, SD = 1.08$ ) and low-performance group ( $n = 104, M = 1.94, SD = 1.37$ ),  $p = .008$ , but no other group differences were significant.

#### *Online resources (e.g., ArcGIS Help, websites)*

Students who ranked online resources as being more helpful to GIS learning often commented about the accessibility of information. For example, students indicated that online resources, particularly Google and ArcGIS Help, were helpful because information on technical terms and definitions, as well

as similar problem-solving approaches, were easily accessible and available at any time and location. One student commented, “online resources are easily accessible and sometimes there is a forum [of] people discussing the similar problems that I was having difficulties with.” Similarly, another student noted, “the help on ArcMap was very handy while performing tasks, especially in word definition clarifications. ... I always use ArcGIS Help to understand map projections because sometimes I forget which one to use.” For such reasons, online resources were more valued by the higher-performance groups in general.

### *Discussion with peers*

Students described their peer discussion experiences similar to what is typically encountered in liminal spaces (e.g., emotional reactions, mimicry as a coping mechanism). For example, one student mentioned that this learning approach was helpful as a means of “*quickly* [emphasis added] figuring out what should be done.” Since liminal spaces felt time-consuming and frustrating, this student relied on the use of mimicry or surface learning as a coping strategy (i.e., simply following the steps of what others did). Although mimicry does not necessarily entail plagiarism (which is deemed to be an academic offence), it is important to note that plagiarism could be regarded as an extreme case of mimicry where students pretend to understand a threshold concept without its authentic learning.

Some students adopted discussion with peers as a coping strategy and as a virtue of a supportive liminal environment, which helped them to withstand and tolerate confusion and uncertainty involved in learning. One student mentioned, “I thought some questions I had might be unimportant, stupid, or absurd, so discussing with peers helps because we are on the same level ... [and] I feel like I am not the only one who’s struggling.” Another student also implied that discussion with peers was encouraging in confronting and dealing with troublesomeness when they were stuck: “It was more engaging when we encountered the same problems. ... Discussion with peers encouraged me for testing out the theory by many trial and errors working together in the lab [*sic*].” In other words, sharing ideas or reflections with peers helped these individuals to reveal common difficulties or anxieties. Therefore, the surface learning approach can be used as a strategy for providing emotional support when dealing with troublesomeness. However, students heavily relying on discussions with peers may end up overvaluing a surface learning approach, addressing the issues of mimicry or lack of authenticity.

As previously mentioned, discussion with peers was found to be more valued by the lower-performance groups. One possible explanation might be due to the issues of mimicry or lack of authenticity. In addition, peers may constantly struggle with *solving* the problems, due to their limited knowledge or

understanding: “Discussing with peers is just speculating and guessing that answer among yours. ... [So] it might not be as helpful because other peers may also not know or we are all just confused about it.”

### *Lectures and lecture notes*

The higher-performance groups more valued lectures and lecture notes as their primary learning resources. Students indicated that these learning resources helped them to first establish a concrete disciplinary understanding and foundational knowledge: “Lecture notes introduce you [to] the theoretical and basic knowledge ... [which are] the important things you have to know. ... When we are stuck, we can refer back to the lecture notes to refresh our memories.” One important aspect of this approach was associated with linking a theory-practice gap (i.e., effectively applying conceptual understanding throughout the hands-on lab activities): “I prefer to [first] learn by going through conceptual materials rather than just doing the lab assignments which you don’t understand.”

Furthermore, students often commented about the benefit of lectures for observing demonstrations or examples provided by the course instructor. In the case of GEOG/PLAN 281, students were taught, for example, an orange-peeling demonstration to facilitate their understanding of map projections:

“The orange-peeling demonstration shown in the class was really helpful, as it was [visually] relatable. It made me easy to understand that we can never have a complete perfect level of peel or map projections. So no map is perfect but it has to be more focused on what you want to see. ... I feel that pictures and other types of *visuals* [emphasis added] would aid a lot in learning, rather than just using descriptive words.”

Visual demonstrations were helpful as a constructivist response to the forms of troublesome knowledge that students may experience (e.g., *conceptually difficult, counter-intuitive knowledge*). Therefore, students who valued lectures and lecture notes as primary learning resources were offered an opportunity to observe such demonstrations and to pick up relatable examples.

### *Discussion with instructors (e.g., faculty, TAs)*

For discussion with instructors, no significant differences were found between the three performance groups. Nevertheless, it was interesting to note that the low-performance group placed relatively more value on discussion with *peers* ( $n = 104, M = 4.30, SD = 1.43$ ) than on discussion with *instructors* ( $n = 104, M = 3.81, SD = 1.60$ ), while the high-performance group had relatively more-balanced perspective on discussions with both peers ( $n = 114, M = 3.80, SD = 1.49$ ) and instructors ( $n = 114, M = 3.66, SD = 1.52$ ). For example, students who more valued discussion with instructors

explained that instructors were more knowledgeable in terms of providing the *right* or *appropriate* instructions or guidance. These students noted that discussion with instructors encouraged them to think more critically and problem-solve, because they provided an idea of where to begin rather than just providing direct answers.

#### *Tutorial instructions/sheets*

There are several reasons why tutorial instructions/sheets were relatively less valued by the majority of students for all performance groups. As noted earlier, establishing a concrete, conceptual understanding of the subject matter was crucial *before* applying them in hands-on lab assignments. In other words, a theory-practice gap may exist if students attempt to perform hands-on lab activities without a clear conceptual understanding. Another reason was associated with the step-by-step format of tutorial materials offered in the introductory course: “These instructions only tell you steps, and it’s hard to understand the bigger picture without understanding the theories behind [them].” In this respect, students suggested that the application part of learning through lab assignments should come after lectures in order to obtain a more concrete, understanding of the overall concept. Although no statistical significance was observed, it is still important to note that the high-performance group ( $n = 114$ ,  $M = 3.46$ ,  $SD = 1.68$ ) placed more focus on the tutorial instructions than the low-performance group ( $n = 104$ ,  $M = 3.32$ ,  $SD = 1.55$ ). In summary, students who valued a more balanced understanding of theoretical knowledge and their applications were more proficient in GIS learning.

#### *Library resources (e.g., books)*

Library resources were found to be the least helpful method of GIS learning for all performance groups. Students commented that they felt library resources were time-consuming because many other resources were easily accessible and already sufficient for their understanding of the subject matter. One student indicated, “I didn’t really use library resources. I didn’t feel like I needed to go to library because resources were already available online. ... I think lecture notes already had enough information.” Similarly, another student mentioned, “I could spend hours finding books about some information that I could find just by typing on Google.” Therefore, the accessibility of information (i.e., for saving time) was an important factor for students’ learning approaches.

#### **4.2.2.4 Differences Between Semester Cohorts**

In different semester cohorts, certain student characteristics can shape the groups’ perceptions or attitudes towards their GIS learning. Since different groups of students undertake GEOG/PLAN 281

each semester (i.e., every academic year is comprised of three seasonal semesters: Winter, Spring, and Fall), inter-seasonal variations were examined in terms of differences between semester cohorts. These differences were assessed based on student characteristics that affect how students deal with liminal spaces, namely: (1) student backgrounds; (2) ArcGIS software learning; and (3) learning resources.

1) *Student Backgrounds*

In Section 4.2.1, important student backgrounds for attaining proficiency in GIScience were identified, including academic preparedness, educational status, study major, type of academic background, and prior subject learning experiences in mathematics, GIS, programming, or computer science. In Sections 4.2.2.1 and 4.2.2.2, these backgrounds were assessed in terms of how they may have affected variations in students’ ways of thinking and practising throughout liminal spaces. These backgrounds are further assessed in terms of how they vary between semester cohorts.

*Academic Preparedness*

A chi-square test for association indicated that students’ academic preparedness was dependent upon inter-seasonal academic semesters,  $X^2(4) = 27.85, p < .001$ . As shown in Figure 4.10, the greatest proportion of students who self-rated as being fully prepared or confident to undertake GIS learning was in the Fall terms ( $n = 56$  of 299, 19%), while this was halved in the Spring terms ( $n = 35$  of 374, 9%). Alternatively, the greatest proportion of students who self-identified as being not prepared was in Spring ( $n = 179$  of 374, 48%). All in all, students’ self-rated academic preparedness was considerably lower in Spring compared to other terms. Therefore, students undertaking GEOG/PLAN 281 in Spring may require more support to gain foundational background knowledge in GIScience.

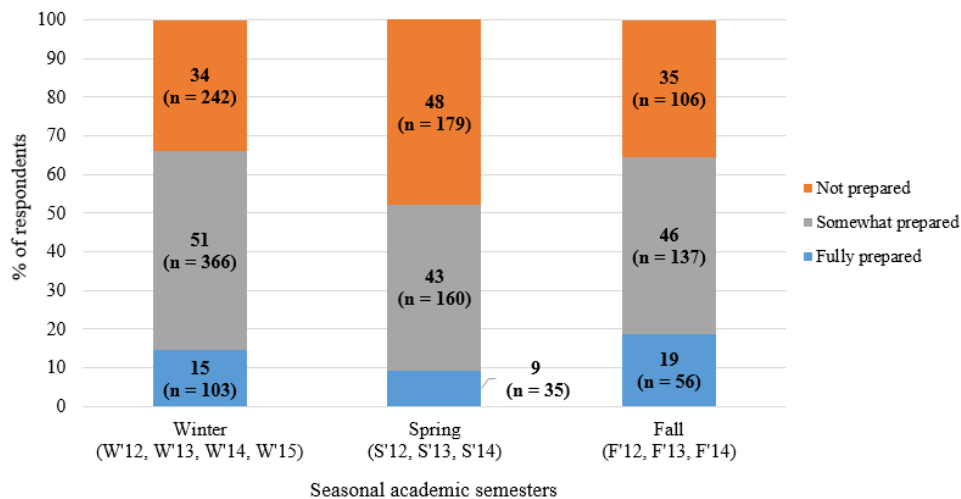


Figure 4.10 – Students’ academic preparedness by inter-seasonal academic semesters of Winter’ 12-15, Spring’ 12-14, and Fall’ 12-14.

### Educational Status

A chi-square test indicated that students' educational status was dependent upon inter-seasonal semesters,  $X^2(4) = 98.82, p < .001$ . As shown in Figure 4.11, the greatest proportion of third-year or later students were enrolled in the Fall semesters ( $n = 86$  of 293, 30%), followed by the Spring ( $n = 94$  of 371, 25%) and Winter ( $n = 160$  of 701, 23%) semesters. First-year undergraduate students also made up the highest proportion in Fall terms ( $n = 77$  of 293, 26%), followed by Winter ( $n = 174$  of 701, 25%). However, only 3% of first-year students enrolled in GEOG/PLAN 281 during Spring ( $n = 11$  of 371). Instead, second-year undergraduate students were dominant in Spring semesters ( $n = 266$  of 371, 72%). Thus, there was a good mixture of lower- and upper-year students in Fall and Winter terms, but students in Spring were predominantly from second-year studies.

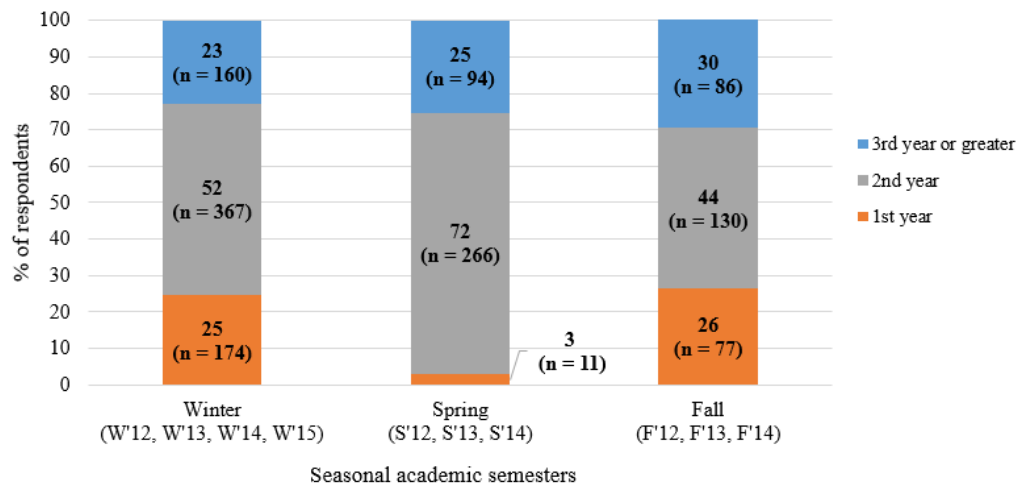


Figure 4.11 – Students' educational status by inter-seasonal academic semesters of Winter'12-15, Spring'12-14, and Fall'12-14.

### Major Field of Study

According to a chi-square test, students' major field of study varied significantly between semesters,  $X^2(8) = 572.37, p < .001$ . As shown in Figure 4.12, about half of students enrolled in Winter terms were majoring in geomatics and planning ( $n = 342$  of 695, 49%), while fewer students were enrolled in Fall ( $n = 27$  of 286, 9%) and Spring ( $n = 14$  of 363, 4%). On the other hand, Spring students were predominantly from environment and business ( $n = 262$  of 363, 72%) with fewer in Fall ( $n = 91$  of 286, 32%) and Winter ( $n = 104$  of 695, 15%). Half of the class in Fall terms ( $n = 143$  of 286, 50%) comprised of students majoring in physical geography-related fields (e.g., geography, earth and environmental sciences, environmental and resource studies), while fewer (21%) were enrolled in both Winter ( $n = 144$  of 695) and Spring ( $n = 76$  of 363) terms. Moreover, 12% of students were majoring in

aviation in Winter ( $n = 84$  of 695), and only 5% in Fall ( $n = 13$  of 286), but none of them took GEOG/PLAN 281 in Spring terms. No significant seasonal variation in enrollment was found among students majoring in computer science/engineering/mathematics, which collectively formed a relatively small cohort.

As discussed in Sections 4.2.1 and 4.2.2.1, environment and business students were considerably less competent in GIS learning than those from geomatics/planning programs. This may be due to the lesser extent in which they can relate to the subject from their major fields of study (i.e., less previous exposure to GIScience-related concepts). In this regard, students undertaking GEOG/PLAN 281 in Spring may lack the background and experience required for productively moving through their liminal spaces (i.e., by finding the relevance for necessary scaffolding and meaningful learning) compared to other semesters. They may also be relatively less familiar with the subject matter of GIScience and less prepared to undertake learning in this subject.

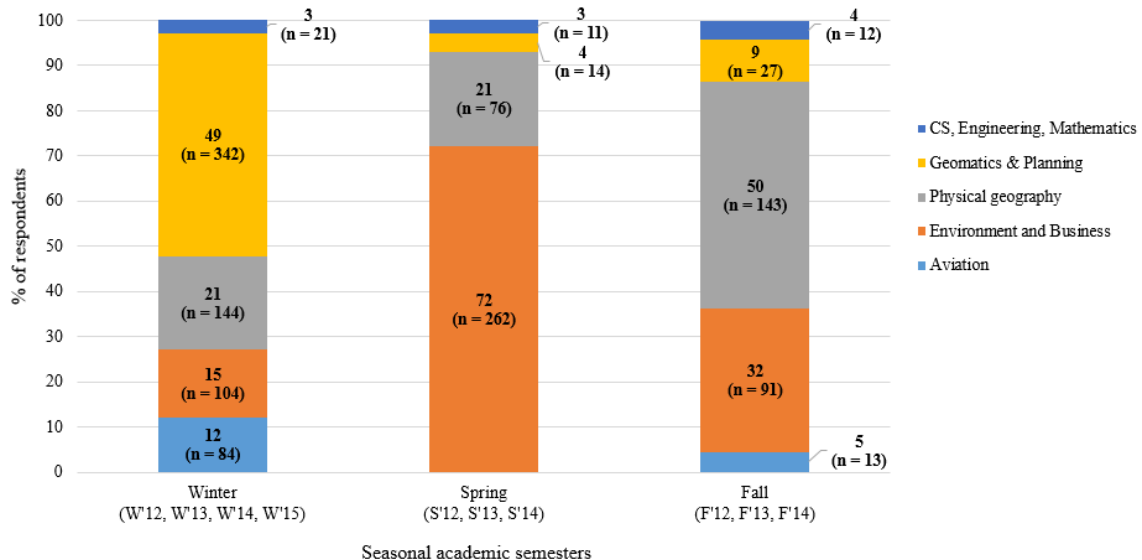


Figure 4.12 – Students’ major fields of study by inter-seasonal academic semesters of Winter’12-15, Spring’12-14, and Fall’12-14.

### *Type of Academic Background*

A chi-square test showed that students’ type of academic background varied significantly between semesters,  $X^2(4) = 28.14$ ,  $p < .001$ . As shown in Figure 4.13, students with a quantitative academic background undertook GEOG/PLAN 281 mostly during Fall terms ( $n = 91$  of 299, 30%), followed by Winter ( $n = 142$  of 711, 20%) and Spring ( $n = 58$  of 374, 16%). In contrast, multidisciplinary students took the course mostly in Winter ( $n = 369$  of 711, 52%), followed by Spring ( $n = 184$  of 374, 49%) and Fall ( $n = 122$  of 299, 41%). The greatest proportion of students with a qualitative academic background was in Spring ( $n = 132$  of 374, 35%), followed by Fall ( $n = 86$  of 299,

29%) and Winter ( $n = 200$  of 711, 28%). Therefore, compared to other terms, Spring semesters students tended to have lesser quantitative aptitude, experience, and capability, which may be crucial for proficient GIS learning (i.e., dealing with numerical data and understanding the complexity behind underlying mapping processes). This may correspond with the environment and business program students who tended to take GEOG/PLAN 281 during Spring terms and who likely come from qualitative backgrounds in the arts and/or humanities. From a teaching perspective, students undertaking GEOG/PLAN 281 during Spring terms may require more attention and support for overcoming knowledge barriers, perhaps by providing additional fundamental training on basic quantitative concepts and technical aspects of GIS learning.

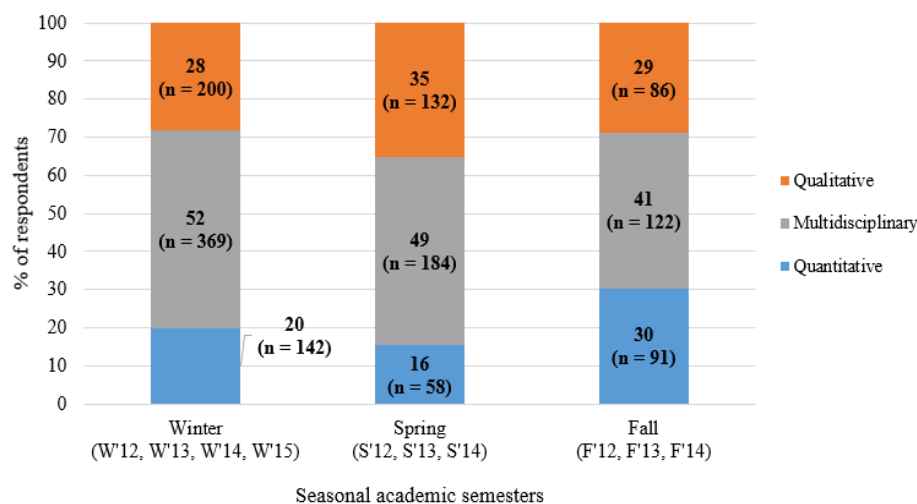


Figure 4.13 – Students’ type of academic background by inter-seasonal academic semesters of Winter’12-15, Spring’12-14, and Fall’12-14.

#### *Prior Subject Learning Experiences*

A chi-square test identified significant inter-seasonal semester variations in whether students had prior subject learning experiences in math, GIS, programming, and computer science:  $X^2(2) = 12.66$ ,  $p = .002$ ;  $X^2(2) = 32.36$ ,  $p < .001$ ;  $X^2(2) = 19.27$ ,  $p < .001$ ; and  $X^2(2) = 16.91$ ,  $p < .001$ , respectively. As shown in Figure 4.14, students undertaking GEOG/PLAN 281 in Fall terms had relatively less-extensive backgrounds in math than those in other semesters. However, the proportions of students with prior learning in computer science, programming, and GIS were the greatest in Fall. Students in Spring had more background in math (perhaps due to a larger environment and business student cohort, who have economics and marketing training), although these students had considerably less prior experience with GIS, programming, and computer science. The findings in Sections 4.2.2.1 and 4.2.2.2 indicate that all of these prior learning experiences are crucial for students’ gaining proficiency in GIS learning. Therefore, students undertaking GEOG/PLAN 281 in Spring may require additional support to reinforce foundational background knowledge in GIS, programming, and computer science.

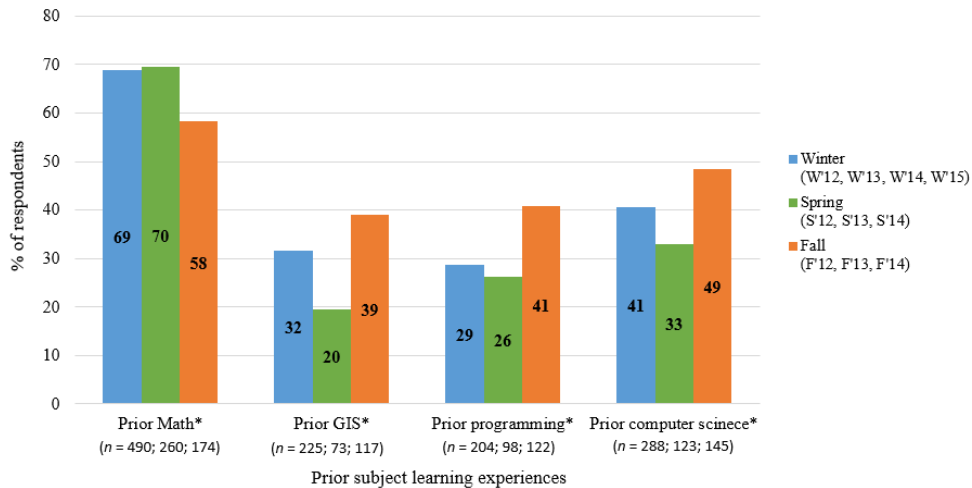


Figure 4.14 – Students’ prior subject learning experiences by inter-seasonal academic semesters of Winter’12-15, Spring’12-14, and Fall’12-14 (\* $p < .05$ ).

## 2) ArcGIS Software Learning

A chi-square test indicated that students’ difficulty in learning the ArcGIS software varied between semesters,  $X^2(4) = 8.74, p = .068$ . In other words, students tend to experience learning ArcGIS software differently in different seasonal semesters. For example, as shown in Figure 4.15, the proportion of students finding the software difficult to learn was the greatest in Spring ( $n = 136$  of 374, 37%), followed by Winter ( $n = 248$  of 711, 35%) and Fall ( $n = 93$  of 299, 31%). This pattern was the same for those students who found software learning neither difficult nor easy (i.e., neutral). On the other hand, students finding the software easy to learn were mostly enrolled in Fall ( $n = 72$  of 299, 24%), followed by Winter ( $n = 140$  of 711, 20%) and Spring ( $n = 57$  of 374, 15%). Therefore, Spring semester students may require additional support in terms of software tutorial guidance in order for students to navigate effectively through and learn the practical use of ArcGIS software.

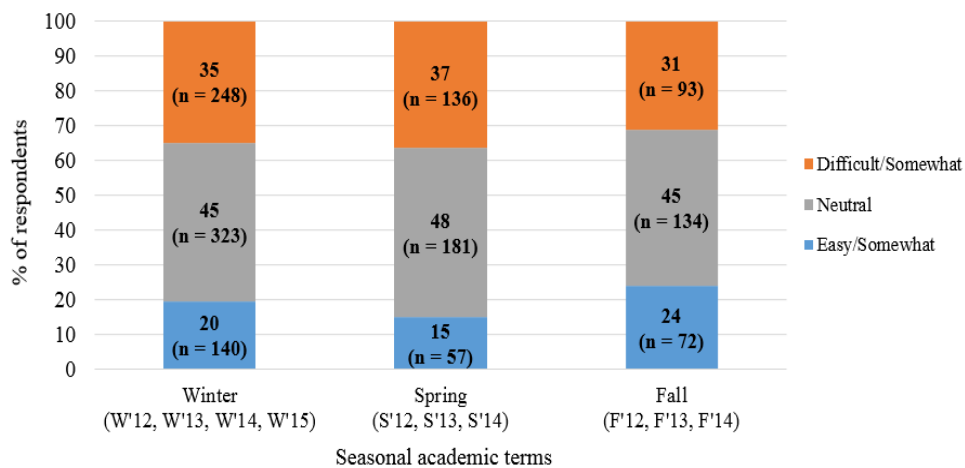


Figure 4.15 – Students’ difficulty rating of the ArcGIS software by inter-seasonal academic semesters of Winter’12-15, Spring’12-14, and Fall’12-14.

### 3) GIS Learning Resources

As assessed by a one-way ANOVA, the average ranking score of helpfulness for the following learning resources differed significantly between inter-seasonal semesters: lectures and lecture notes,  $F(2, 1350) = 5.83, p = .003$ ; discussion with instructors,  $F(2, 1350) = 11.81, p < .001$ ; and tutorial instructions/sheets,  $F(2, 1349) = 6.68, p = .001$ . In previous sections and analyses, the findings suggest that students undertaking GEOG/PLAN 281 in Spring may require additional support. As a result, Spring semester students were exclusively examined as an exploratory investigation. In Section 4.2.2.3, lectures and lecture notes were found to be highly valued by the higher-performance groups. In comparison, as shown in Figure 4.16, students undertaking GEOG/PLAN 281 in Spring tended to utilize and value these learning resources less than students in other terms. Therefore, perhaps lectures and lecture notes provided to students in Spring could be augmented with more demonstrations and examples (i.e., in the area of environment and business) in order to facilitate their motivation and engagement in scaffolding and meaningful learning in the course.

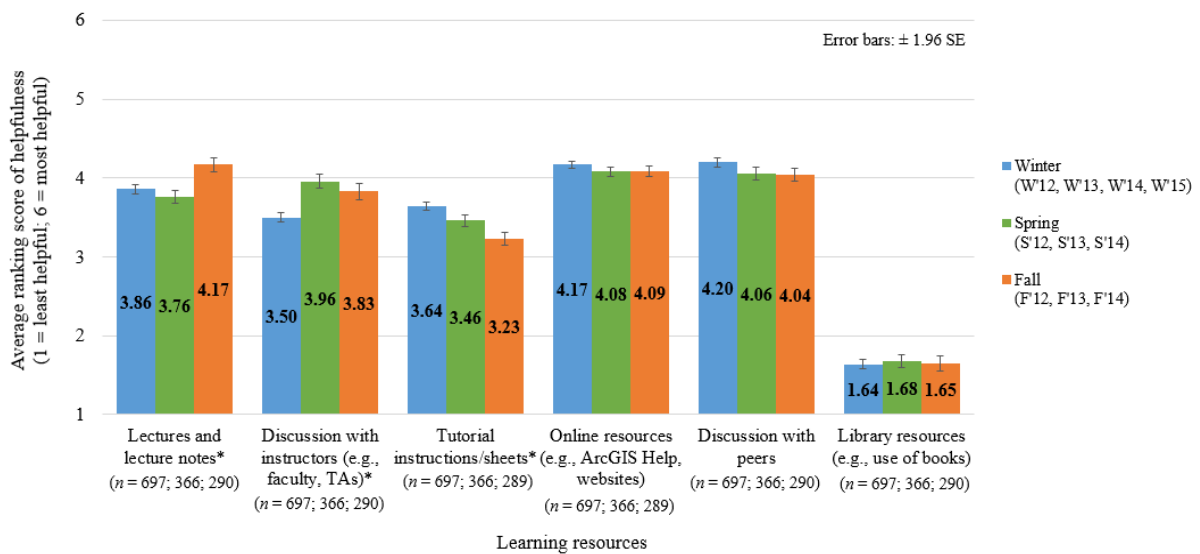


Figure 4.16 – Students’ average ranking score of helpfulness for learning resources by inter-seasonal academic semesters of Winter’ 12-15, Spring’ 12-14, and Fall’ 12-14 (\* $p < .05$ ).

#### 4.2.4 Post-liminal Variation: Potential Implications for STEM

In terms of post-liminal variation, the potential implications of students’ proficiency in GIS learning (i.e., crossing thresholds) are discussed with respect to STEM education. In this analysis, the performance groups for GEOG/PLAN 281 were assessed based on the notion that those who acquire threshold concepts would be “inside” the subject. Again, it was assumed that those in the higher-performance groups were more likely to have successfully negotiated and moved through the liminal spaces and gained distinctive disciplinary ways of thinking (i.e., inaccessible for novice learners).

First, students' spatial thinking abilities were gauged based on the STAT instrument, as described in Section 3.3.1. The total possible score with this instrument is eight (i.e., one score for one question). This instrument was added to the GIS Education User Questionnaire in Fall 2014 and continued in following terms. Out of a total of 242 respondents (Fall'14 and Winter'15), the average spatial thinking score was 5.50. As shown in Figure 4.17, students in the high-performance group in GIScience had a higher average spatial thinking score ( $n = 53$ ,  $M = 6.15$ ,  $SD = 1.25$ ), followed by those in the intermediate ( $n = 167$ ,  $M = 5.38$ ,  $SD = 1.67$ ) and low-performance ( $n = 22$ ,  $M = 4.82$ ,  $SD = 1.68$ ) groups. A one-way ANOVA confirmed that this difference was statistically significant,  $F(2, 239) = 6.97$ ,  $p = .001$ . All pairwise comparisons by the Tukey post-hoc test were statistically significant derived from the difference between the high-performance and intermediate ( $p = .006$ ) groups, as well as the difference between the high-performance and low-performance ( $p = .003$ ) groups. However, the difference between the intermediate and low-performance groups was not significant.

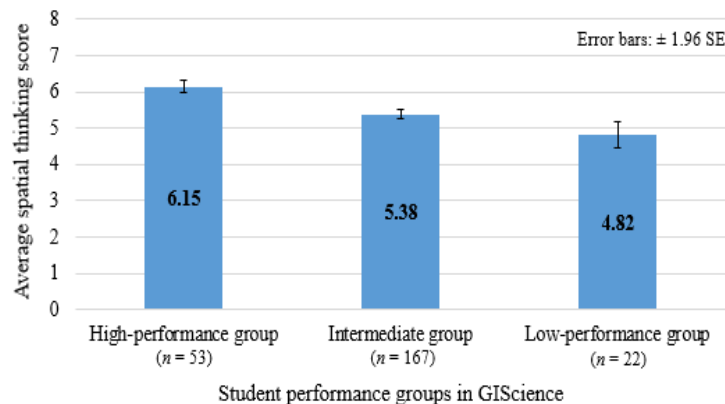


Figure 4.17 – Students' average spatial thinking scores by their performance groups in GIScience.

Results from this study support that the high-performance group in GIScience (i.e., those who productively moved through the liminal spaces and achieved a new, deeper level of disciplinary understanding) was comprised of more spatially oriented students (i.e., those with the geographic foundation of thinking spatially) than in lower performance groups. Thus, it is evident that critical spatial thinking occurs in the minds of experienced or competent GIScience students. For example, one student commented that GIS learning augmented the ability to think spatially: “Focusing on spatial information and related concepts [in GIScience] has encouraged me to think spatially. I now try to look for spatial trends in certain phenomena like disease outbreaks.” Another student also noted,

“Before I took this course, spatial information was not that significant in my perception. ... I tend to engage more spatial factors in my thinking now. ... I think a lot more about how things in real life are spatially connected ... [and] influence each other. ... [So,] my thinking is now more spatially oriented, and I grasp the concepts in my major better because they are spatial concepts.”

Students described new spatial perspectives acquired from GIS learning as, “I now see the importance of conveying information spatially,” “Now I am more spatially aware,” and “I see things more spatially.” In the earlier Section 4.1.3, students’ transformative episodes of learning were explained in terms of how acquiring GIScience threshold concepts helped to open up new ways of thinking, especially for critical spatial awareness in mapping (i.e., ways of looking at a map).

The problem-solving contexts of students’ spatial skills (e.g., visualization, spatial thinking) within GIScience were found to be associated with student interest and competency in other STEM-related fields. First, in the survey questionnaire, students were asked to indicate whether they currently had an interest in STEM fields for pursuing their academic or career goals. Overall, the majority of students ( $n = 95$  out of 242, 39%) indicated “maybe/somewhat” for their current interests in STEM, whereas 29% ( $n = 69$ ) had interests in STEM and 32% ( $n = 78$ ) did not have such interests. According to a chi-square test, student interest in STEM varied significantly between performance groups in GIScience,  $X^2(4) = 11.22$ ,  $p = .024$ . As shown in Figure 4.18, the higher-performance groups in GIScience were comprised more of students with an interest in STEM education for pursuing their academic or career goals. On the other hand, the reverse pattern was found for the lower-performance groups with more students indicating no interest in STEM fields.

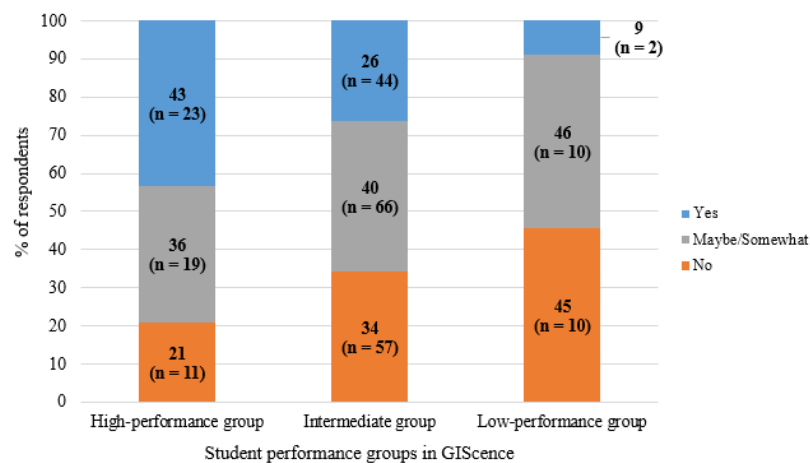


Figure 4.18 – Students’ current interest in STEM by the performance groups in GIScience.

Students were asked whether they agreed/disagreed that spatial skills and critical thinking/problem-solving skills from GIS learning experiences fostered their interest and self-confidence in pursuing STEM fields. To create more meaningful categories for a comparative analysis, the frequency of responses for “Strongly agree (disagree)” and “Agree (Disagree)” were combined into a single “Agree (Disagree)/Somewhat” category. According to a chi-square test, students with an interest in STEM tended to agree with the two statements (see Figure 4.19),  $X^2(4) = 27.93$ ,  $p < .001$  and  $X^2(4) = 20.77$ ,  $p < .001$ , respectively.

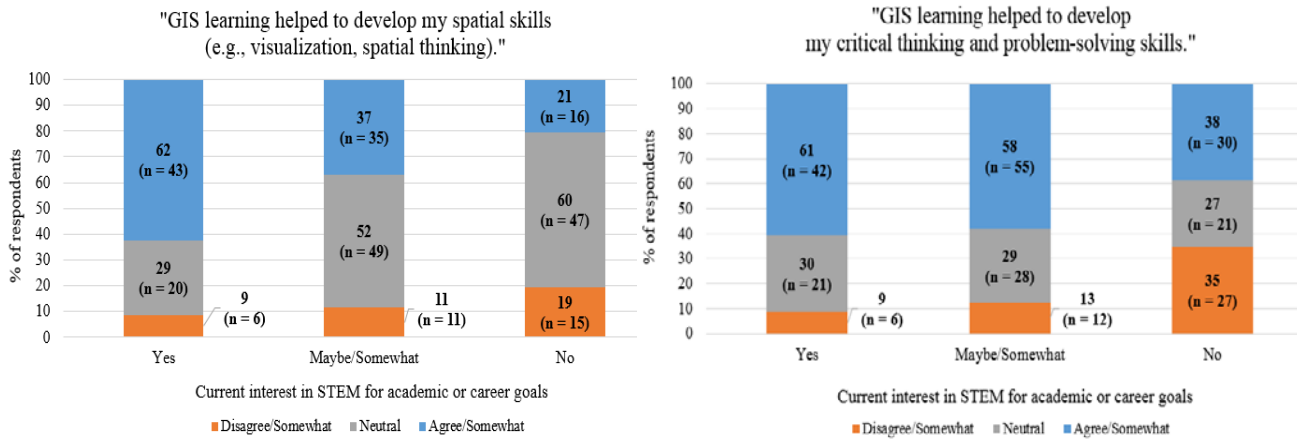


Figure 4.19 – Students’ current interest in STEM and their levels of agreement/disagreement with the statements relevant to the GIS learning experiences: spatial skills (left) and critical thinking and problem-solving skills (right).

Students with GIS learning proficiency (i.e., those who productively moved through liminal spaces) developed their spatial skills as well as critical thinking and problem-solving skills. This ultimately led to a positive feedback, also augmenting their interest and self-confidence in other STEM-related fields:

“The ability to think spatially and apply various problem-solving techniques to different situations is a very important skill [that I gained from this course]. ... GIS allowed me to view, understand, question, interpret, and visualize data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. It also helped me to answer questions and solve problems by looking at [and working with] the [spatial] data. ... Being able to put stuff into a software to visualize something made me feel accomplished and gave me an interest in the technological side of working with GIS.”

“The problem-solving experience in the use of technology for applying the concepts gave me the confidence and interest [in STEM fields]. ... When there were errors, I tried to explore to solve the problems. ... The labs did enhance my critical thinking to determine how to accomplish the assigned task [in creating maps]. ... It helped me to learn something more about programming and technological aspects of geography ... [and] to think that I can do more now.”

Students indicated that extending their use of technical language through GIScience learning made them feel more confident and competent to undertake learning in STEM fields. For example, they commented that extension of subject-specific technical language made them feel better able to communicate in the community of practice (see Sections 4.1.3 and 4.2.2.2). This is likely associated with the bounded feature of threshold concepts, observed in the post-liminal state after moving through liminal spaces.

Students further indicated that their GIS learning helped them realize the importance of new emerging technologies used in diverse application areas (i.e., appreciation of GIS for societal needs and daily-life

operations in practical fields). As shown in Figure 4.20, 164 students indicated an interest (“Yes” or “Maybe/Somewhat”) for pursuing STEM fields. The most frequently cited career goal was the private sector (e.g., corporate, consultancy) ( $n = 50$ , 30%), followed by the public sector (e.g., government) ( $n = 46$ , 28%), uncertain or do not know ( $n = 44$ , 27%), and others (e.g., academia, non-profit sector) ( $n = 24$ , 15%). The majority of these STEM-oriented students consisted of those seeking job opportunities and potential earnings in general. For example, one student commented about appreciating GIS learning as follows: “It gives a better outlook on job perspectives and what you can do in the future ... [for] the job market [in] demand.” Similarly, another student noted, “when I was searching for jobs, I noticed all different ways of applying GIS to different things. So I felt like a lot of opportunities were opened to me. ... I think GIS skills are useful that would support my employability.”

In the survey questionnaire, students were asked to indicate one application area in which GIS would potentially be useful. Only those who had some interests in pursuing STEM fields ( $n = 164$ ) were examined. Evidently, the most prominent application area was found to be in urban planning/development ( $n = 84$ , 52%):

“From the planning perspective, I think GIS has a lot of power ... as a tool to collect and display data. ... I appreciate the way GIS can help ... create demonstrative maps as a way to showcase ideas and data in a decision-making process ... [especially] looking at the geography of the development area. ... I think more about sociological impacts how certain infrastructures would affect the agricultural communities. ... It is essential for urban planners to use maps and communicate [visual] information accurately [with the public]. ... [So,] I will definitely take what I have learned in this class and use it in the future.”

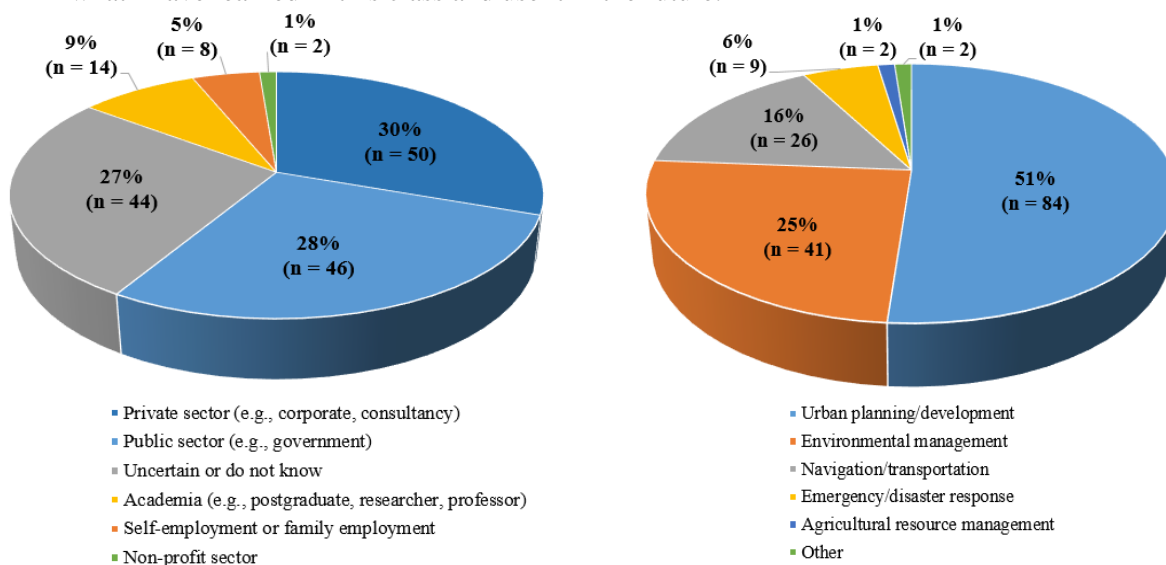


Figure 4.20 – Career goals (left) and most useful application areas of GIS (right) indicated by students interested in pursuing STEM fields.

Finally, the capabilities of GIS to visually analyze and portray geographic features can act as an interactive medium. For example, students who appreciated the creative and artistic aspects of GIS found STEM fields to be more accessible:

“[I realized that] maps are not as simple as black and white. In reality, there is a *science and art* [emphasis added] required to create them. ... I had a very difficult learning curve. ... However, I stuck with it and it paid off. ... Once you understand the theory and concepts, the [GIS] program actually becomes fun and you get to discover more. ... I really started enjoying the process of creating maps and learning about how maps affect the world around us.”

Therefore, students’ gaining proficiency in GIS learning can ultimately encourage them to learn other STEM-related fields. This may be achieved through enhanced spatial thinking abilities, as well as adopting creativity, critical thinking, and problem-solving skills. This mutual relationship and feedback process may be beneficial in attracting individuals with diverse backgrounds to the fields of GIS and meeting the growing demands for a skilled workforce in the community of practice.

#### **4.4 CHAPTER SUMMARY**

This chapter presented empirical evidence of a threshold concept framework in GIScience, as well as its potential implications for STEM. The investigation of the framework mainly relied on the troublesome and transformative characteristics of threshold concepts. Based on the participants who indicated particular knowledge areas as challenging, their ranking of difficulty regarding key concepts was further examined. These challenging concepts formed a basis for narrowing down and identifying potential threshold concepts. The most prominent threshold concepts were then identified based on students’ transformative learning experiences: *map projections* and *advantages and disadvantages of raster and vector data models*. Overall, the transformative episodes in learning these threshold concepts were found to be associated with student perspectives of maps (i.e., ways of looking at a map). In terms of pre-liminal variation, important student background factors for the discipline were identified, including academic preparedness, educational status, study major, academic background type, and prior learning in mathematics, GIS, programming, and computer science. For liminal variation, the role of such background factors was assessed with respect to their importance when moving through liminal spaces. In a similar manner, students’ GIS software experience and learning resources were evaluated. Inter-seasonal variations were evident, since students undertaking GEOG/PLAN 281 in Spring seemed to encounter more challenges when gaining proficiency in GIScience learning. For post-liminal variation, students who successfully crossed learning thresholds in GIScience were able to improve their spatial thinking abilities and gain more interest and self-confidence in pursuing further learning in STEM fields.

## CHAPTER 5 DISCUSSION AND CONCLUSIONS

This present exploratory study set out to investigate empirical evidence of the threshold concept framework in GIScience and its potential implications for STEM education. The main research objectives include the following: (1) to explore common troublesome knowledge and threshold concepts identified by GIScience students; (2) to examine variations in students' ways of thinking and practising within GIScience; and (3) to discuss potential implications of threshold concepts and proficiency in GIS learning on other STEM-related fields. This chapter summarizes key research findings to interpret and explain answers to the research questions. Then, the study limitations are discussed and suggestions are offered for future work. Finally, this chapter concludes by reflecting upon the potential contribution of this study to the research community.

### 5.1 SUMMARY OF FINDINGS

#### 1) *A Threshold Concept Framework in GIScience*

The first research question investigated in this study was, “What are common troublesome knowledge areas and threshold concepts in GIScience?” Answering this question relies on identifying the troublesome and transformative criteria of threshold concepts. Other mutually interdependent features – irreversible, integrative, and bounded – are then assessed to further support the empirical evidence of identifying threshold concepts. This study adopted the *Decoding the Disciplines* approach (Middendorf & Pace, 2004) to identify bottleneck candidates where students are likely to get stuck in their learning. The rationale behind this approach was to first narrow down potential threshold concepts based on the notion that troublesome knowledge indicates the existence of a threshold (Meyer & Land, 2003; Shopkow, 2010). Thus, focusing on a narrower list of potential threshold concepts, the transformative criterion was then assessed to determine which of these concepts were mostly common in students' transformative episodes of learning (i.e., whether a threshold crossing had occurred) (Meyer & Land, 2003).

Based on a total of 1,384 participants (Winter'12 – 15), the top three most challenging GIS knowledge areas perceived by students were found to be *spatial data modelling and analysis*, *raster data analysis*, and *georeferencing*, which are then followed by *data sources and acquisition*, *data quality*, *vector data analysis*, and *data models* (e.g., *vector and raster*). This study focused on the participants who perceived particular knowledge areas as challenging to further examine their ranking of difficulty regarding key

concepts for each area. This process helped to narrow down and identify all potential threshold concepts that tend to be troublesome for students. These concepts were then used as pre-determined coding categories in the thematic analysis of open-ended survey questionnaire responses and personal interview transcripts. Ross et al. (2010) suggest that “what is a threshold concept for one student may not be a threshold for another” (p. 47) due to variations involved in liminal spaces (Meyer, Land, & Davies, 2008). Therefore, in thematic analysis, the frequency counts of the threshold concepts indicated by individual students (i.e., based on their transformative learning experiences) were combined to identify the most frequently occurring ones. Other studies also adopted a similar approach in focusing on the most-prominent threshold concepts as exploratory examples (e.g., Davies & Mangan, 2005; Shanahan & Meyer, 2006; Srivastava, 2013).

More specifically, *map projections* and *advantages and disadvantages of raster and vector data models* were found to be the most prominent threshold concepts identified by GIScience students. In GEOG/PLAN 281, *map projections* were mainly addressed in the georeferencing knowledge area, and *advantages and disadvantages of raster and vector data models* were primarily covered under the topic of spatial data modelling and analysis. Interestingly, these knowledge areas were frequently indicated as challenging for students. Since grasping threshold concepts leads to learners’ deeper levels of disciplinary understanding for a particular topic (Ashwin, 2008; Davies & Mangan, 2007; Meyer & Land, 2003; Lucas & Mladenovic, 2006), this empirical evidence supports the notion that troublesome knowledge indicates the existence of a threshold (Meyer & Land, 2003; Shopkow, 2010). However, unexpectedly, no bottleneck candidates in the topic of *raster data analysis* were identified by students as thresholds. One possible explanation is that these bottleneck candidates may be simply difficult core concepts that lack the transformative quality needed to affect students’ ways of thinking about the discipline. This explanation is also supported by Meyer and Land (2006a, p. 6): “[unlike threshold concepts,] core concepts do not necessarily lead to a qualitatively different view of subject matter.”

More importantly, the research findings revisit the work of Srivastava (2013), a primary pioneer who proposed a theoretical foundation for threshold concepts in the field of GIScience. As mentioned in Section 2.2, Srivastava (2013) proposed GIS threshold concepts as *data models*, *interoperability*, and *map scale*. However, it is important to note that this previous study identified and examined threshold concepts from the expert point of view, based on summative content analysis of seminal GIS research papers. According to threshold concept theory (i.e., the irreversibility criterion), such concepts should be explored from learner perspectives, because it is difficult for teachers and experienced experts within a discipline “to gaze backwards across thresholds and understand the conceptual difficulty or obstacles

that a student is currently experiencing” (Land et al., 2006, p. 199). After a literature review was conducted, virtually no studies exist with empirical evidence for supporting the threshold concept framework in GIScience from student perspectives. Therefore, this study targeted introductory GIScience undergraduate students and collected empirical findings that supplement current knowledge about the GIScience threshold concept framework.

The empirical results support Srivastava’s (2013) finding that *data models* are considered to be a threshold concept in GIScience. By understanding the types of data models and their limitations, the transformative criterion was associated with students’ changed view of maps (e.g., valuing the use of appropriate data models for spatial data analysis and modelling). As discussed in Section 4.1.3, this empirical finding supports the conclusion by Srivastava and Tait (2012) that such transformative learning experiences in GIScience can refine students’ spatial or geographic perspectives (i.e., their ways of looking at maps). Such a transformed internal view was found to be irreversible, since students noted that, thereafter, they tended to recognize types of data models whenever looking at a map.

However, unexpectedly, the integrative nature of this threshold concept suggested in Srivastava’s (2013) work was found to be inconsistent in this study. For example, during the concept-mapping activity, evidence for students’ selection of *map scale*, *coordinate systems*, *metadata*, *query operations*, and *overlaying* was insufficient in complementing their understanding of the *advantages and disadvantages of raster and vector data models*. This unexpected result may be in part due to different lecture materials (i.e., covering these particular threshold concepts) presented to students. In addition, the survey population consisted of introductory-level GIScience students, and the findings may differ in more advanced GIS courses. On the other hand, the findings were partly consistent with Srivastava’s (2013) in that *data models* were integrative with *errors and uncertainty*. The empirical findings also support and augment evidence of bounded and troublesome characteristics, as discussed in Section 4.1.3.

The study did not examine *interoperability*, a threshold concept proposed by Srivastava (2013), since the author of this study elected to focus only on the conceptual materials covered in the GIS course, GEOG/PLAN 281. However, as discussed in Sections 4.2.2.1 and 4.2.2.2, interoperability was indirectly supported by this study’s empirical results. For example, the findings suggested that prior mathematics, programming, and computer science knowledge and experiences facilitate students’ GIS software learning (i.e., due to familiarity with the terminology and functions of spatial tools). In other words, students were able to explore different ways of extending GIS applications with other disciplinary domains for spatial data modelling and analysis.

Unexpectedly, the study findings do not comply with Srivastava's (2013) consideration of *map scale* as a threshold concept. One explanation might be associated with difficulty rankings regarding key concepts in the survey questionnaire employed in this study. For example, the ranking of difficulty is dependent on the concepts being compared. Results might have been different if *map scale* had been compared with different concepts and found to be more difficult. Nevertheless, *map scale* was identified as being relatively easy to understand by the majority of students (i.e., lack of evidence of a threshold). Thus, this concept was not considered to be a bottleneck candidate in the process of narrowing down potential threshold concepts. Rather, the study suggests that *map scale* is a fundamental building block supporting students' understanding of threshold concepts, particularly *map projections* (i.e., understanding how different map projections are selected depending on map scale). This suggestion is also supported by Anderson and Leinhardt (2002), in which the concept of map scale is linked to students' understanding of map distortions as a consequence of *projection*.

Finally, the study extends the findings of Srivastava (2013) by proposing that *map projections* are the most prominent threshold concept from the perspective of introductory GIScience students. First, as explained in Section 4.1.3, the transformative and irreversible characteristics of this threshold concept were associated with student perspectives of maps (e.g., understanding of the innate error behind map representations). This empirical finding supports the conclusion by Srivastava and Tait (2012) that transformative learning experiences in GIScience can refine students' spatial or geographic perspectives (i.e., their ways of looking at maps). As discussed in the literature review, acquiring threshold concepts can generate a new perspective on other concepts in the discipline (Davies, 2006), and consequently "bind a subject together, being fundamental to ways of thinking and practising in that discipline" (Land et al., 2005, p.54). Shopkow (2010) also argued that difficulties of bottlenecks may be associated with students' failure to fully understand threshold concepts. In this regard, the empirical findings from the concept-mapping activity indicate that *map projections* have such a characteristic for integrating different aspects of the subject. For example, as detailed in Section 4.1.3, grasping map projections complemented students' understanding of other bottleneck candidates (i.e., *map datum*, *modelling the Earth*, *data abstraction*, *uncertainty and error*, and *metadata*). In addition, the findings showed that such integration of subject matter were facilitated by students' understanding of other key concepts (i.e., *map scale*, *coordinate systems*, *geometric measures*, and *accuracy and precision*). Therefore, map projections can act as a facilitating bridge that links students' understandings of the subject matter in GIScience. As discussed in Section 4.1.3, the bounded and troublesome characteristics of map projections were also found to be evident in this empirical study.

## 2) *Variations in Students' Learning Journeys in Liminal Spaces*

The second research question was, “What are the important student characteristics for proficiency in GIScience and how do they account for variations in students’ ways of thinking and practising within GIScience?” This question was raised to respond to a concern addressed by previous studies (e.g., Davies, 2006; Land et al., 2005; Meyer & Land, 2005) with regard to why certain students productively negotiate and pass through liminal spaces, while others find this process to be challenging. Previous studies highlight the importance of exploring and understanding variation in student experiences related to learning threshold concepts. This empirical study assessed four main aspects of variation in students’ GIS learning, namely student backgrounds, ArcGIS software experience, learning approaches, and semester cohorts.

### *Student Background*

As reviewed in Section 2.1.1, grasping threshold concepts can help students to obtain a new, deeper level disciplinary understanding that not only involves a performance element (Meyer & Land, 2003) but also represents their distinctive ways of thinking and practising (Davies & Mangan, 2007; Meyer & Land, 2003; Perkins, 2006). In addition, studies have highlighted that pre-liminal variations (e.g., different prior tacit knowledge, experiences, or disciplinary backgrounds) can affect students’ ways of thinking and practising during the process of learning (e.g., Davies, 2006; Meyer & Land, 2005; Perkins, 1999). In this regard, a statistical analysis was conducted in this study to first identify and assess student background factors crucial for proficient GIS learning (i.e., based on the performance in an introductory GIS course). Results showed that important background factors included student academic preparedness, educational status, major field of study, type of academic background, and prior learning experience in mathematics, GIS, programming, or computer science.

As discussed in Section 4.2.2.1, students’ academic preparedness was found to be associated with their self-confidence in confronting and dealing with the confusion and uncertainty involved in liminal spaces. In this study, it is suggested that student self-confidence, affected by their sense of familiarity with the subject matter, can facilitate motivation or engagement in the self-regulatory process (i.e., dealing with the fear of failure and anxiety). On the other hand, students who felt unprepared lacked such confidence in confronting and dealing with barriers to learning. The results are supported by previous studies. For example, the literature (e.g., Efklides, 2006; Quinnell & Thompson, 2010; Shanahan et al., 2010) shows that students’ self-confidence or familiarity with subject contents (i.e., readiness for learning) can promote the cognitive process for engaging with threshold concepts. Orsini-

Jones (2010) argues that “while they are in the liminal state ... encouraging students to actively engage with metacognition relating to the threshold concept ... can also contribute to their ‘*readiness*’ [emphasis added] to cross it” (p. 282).

Regarding students’ educational status, the findings indicated that third-year or later students undertook GIS learning processes more proficiently than first- and second-year students. This finding is consistent with the conclusions of a previous study (Srivastava, 2010). For example, first-year students underperformed in a GIS course due to a relative lack of study experience. Similarly, Land et al. (2006) found that first-year students had difficulty in grasping threshold concepts due to a relative lack of relevant life experiences. The findings also suggest that students’ educational status was associated with the *extent* to which they had been exposed to *relevant* academic (e.g., foundational knowledge) and career (e.g., co-op) experiences that ultimately influence their level of motivation and engagement.

This study revealed that students’ major field of study was an important background factor for their proficiency in GIScience. However, Srivastava (2010) found the overall effect of students’ disciplinary backgrounds to be not statistically significant on their performance in a GIS course. One possible explanation might be associated with diverse disciplinary groups formed by combining different programs. Srivastava (2010) also commented that this result might be in part due to the tasks (i.e., multidisciplinary nature of GIS applications) used as an assessment of performance. On the other hand, this study examined students’ overall performance in a GIS course as one continuous variable. Notably, the findings were partly consistent with Srivastava’s (2010) results; students in engineering and information and communication technology programs were more proficient in understanding applications of GIS to real-world scenarios. The study also indicated that students majoring in computer science, engineering, or mathematics achieved better academic performance in general. In addition, students majoring in geomatics and planning performed significantly better than those in the environment and business program. As discussed in Section 4.2.2.1, this background factor was associated with students’ scaffolding and meaningful learning. For example, these students were more familiar with the subject matter of GIScience (e.g., use of software, technical terminology) and were more amenable to extrapolating relevant practical applications of GIS to their own fields of study.

Another important factor for student proficiency in GIS learning was associated with their type of academic background (e.g., quantitative, qualitative, multidisciplinary). For example, students from quantitative backgrounds performed significantly better in the GIS course than those from qualitative backgrounds. The findings imply that the mathematical and programming aspects of GIS learning (i.e., dealing with data and numbers and understanding the complexity behind mapping) were facilitated by

students' quantitative aptitudes, experiences, and capabilities. Although quantitative academic backgrounds were found to be more helpful in students' overall success in GIS learning, evidence indicated that those from multidisciplinary backgrounds were able to approach problems and think about threshold concepts from different perspectives (i.e., allowing them to relate to a wider range of applications). In general, this study suggests that stronger quantitative academic backgrounds tend to facilitate students' scaffolding learning for engagement and for their overall success in GIScience (i.e., possibly due to more relatable skills, experiences, and conceptual materials).

The final background factor determined to be significant for influencing student success in GIScience was their prior subject learning experience in mathematics, GIS, programming, or computer science. The findings suggest that such subject knowledge areas and experiences are foundational to student understanding of GIScience (i.e., due to the necessary skillsets, relatable applications, and familiarity with the technical terms/operations). The literature (e.g., Srivastava, 2010, 2013) also suggested that students would require computer, programming and mathematical knowledge if they are to conduct advanced GIS analyses. It is noteworthy that, although relevant prior GIS learning was significant for students' overall success in the introductory GIS course, some students explained that they did not experience transformations in their ways of thinking because a relatively large proportion of the learning content (e.g., threshold concepts) were already familiar to them. Reimann (2004) also found similar evidence, that "if ... everything appears familiar already, the environment is unlikely to provide sufficient stimuli for students to review and revise their existing knowledge [and conceptualizations]" (p. 20).

In contrast, student background factors found to be insignificant for proficient GIS learning included age, gender, native language, geographer type (e.g., human, physical), and prior subject learning experiences in engineering, statistics, cartography, and physical geography. Cousin (2006b) argued that students may experience threshold concepts differently based on their emotional capital (e.g., age, gender). Unexpectedly, the results found these factors to be insignificant in the field of GIScience. In other words, students of different ages or genders were not disadvantaged in undertaking GIS learning and thus in grasping its threshold concepts. Interestingly, although students are likely to be older with higher educational status, the differing age of student groups was not found to be significant, whereas their educational status was found to be significant for proficient GIS learning. In this regard, students' *academic* background can be interpreted to be more important than their *personal* background for crossing thresholds in GIScience.

This study showed that native language was not a significant barrier to students' GIS learning; rather,

the discursive nature or subject-specific technical terminology in the discipline was challenging (i.e., the first shock of troublesomeness due to the *bounded* feature of threshold concepts). This result is consistent with findings from Orsini-Jones (2008), suggesting that “new to me terminology” can be a factor that hinders the process of crossing thresholds. Students’ self-identity in relation to fields of geography (i.e., physical, human) was also not significant, suggesting that students’ different geography mindsets did not influence their GIS learning, at least in an introductory-level GIS course. Similarly, although prior engineering, statistics, cartography, and physical geography knowledge are critical to GIScience (e.g., Bampton, 2012; Fazal, 2008; Srivastava, 2013; Sui, 1995), the results showed that prior knowledge of these disciplines was not significant, although potentially helpful, for GIScience students. This may be associated with the relative simplicity of conceptual materials covered in the introductory-level GIS course (i.e., the course from which the survey sampling was based). For example, statistical knowledge may be a major factor in upper-level GIS courses that deal with more-advanced spatial tools of GIS. These unexpected results may also be partly due to this study’s assumption that students had successfully passed their previous training/courses (i.e., this study did not examine how well students performed in their prior learning).

#### *GIS Software Learning (ArcGIS)*

As discussed in Section 4.2.2.2, students’ ArcGIS software experience was identified as an important factor in the process of moving through liminal spaces. The findings indicated that students who rated ArcGIS as easy to learn are able to better engage in the hands-on lab assignments designed to build their comprehension of GIS theories and concepts. This result is consistent with findings from previous studies (Bain & Bass, 2012; Davies & Mangan, 2008; Srivastava & Tait, 2012). For example, activity-based learning (e.g., integrating principles and practices) can trigger student interest in and motivation for engagement. The software’s visual display of geographic information and its communication of geospatial analysis were found to facilitate student engagement. On the other hand, students who rated ArcGIS as difficult to learn often described their GIS learning as more time-consuming and frustrating (i.e., key characteristics of liminal spaces). These difficulties were found to be associated with the software’s language aspects (e.g., use of technical terminology). This evidence suggests that subject-specific language in GIS software may act as a significant barrier to students’ engagement in learning GIS threshold concepts. Therefore, the results not only support the argument by Srivastava and Tait (2002) that ArcGIS software comes with an easy-to-use graphical user interface, but also suggest that a potential barrier to ArcGIS learning is its use of technical terminology. As discussed earlier, this troublesomeness was related to the discursive and bounded nature of threshold concepts.

### *Learning Resources*

Students move through liminal spaces differently depending on adopted learning resources used to tolerate confusion and uncertainty. In this study, GIS learning resources valued by the majority of students were, in descending order, online resources (e.g., ArcGIS Help, websites), discussion with peers, lectures and lecture notes, discussion with instructors (e.g., faculty, TAs), tutorial instructions/sheets, and library resources (e.g., books).

A comparative analysis by student performance groups indicated that *lectures and lecture notes* were more significantly valued by students in the high-performance group than those in the low-performance group. The value of this learning resource was found to be associated with students' learning opportunities through demonstrations and examples provided in lectures, as well as establishing their own conceptual understanding (i.e., helping to reduce a theory-practice gap). Reimann (2004) found similar evidence regarding the importance of examples and demonstrations (i.e., applications of theory to real-life problems) on students' engagement and motivation. Other previous studies (e.g., Carstensen & Bernhard, 2008; Kinchin et al., 2010) support the findings that students who do not value lecture notes in learning may struggle to effectively apply and link their conceptual understanding to the hands-on lab exercises. Consistent with the literature (e.g., Land et al., 2005, 2006; Srivastava & Tait, 2010), the results also showed that lectures and lecture notes helped students to refresh and develop their conceptual understanding in a *recursive* process of learning threshold concepts.

*Discussion with peers* was found to be less valued by students in the high-performance group than those in the low-performance group. The results were consistent with the findings from Alpay and Masouros (2009), which found that discussion with peers was valued by the majority of students in learning but especially by those who achieved low marks in a subject. Orsini-Jones (2008) support the findings that reliance in group work upon peers can hinder the process of crossing thresholds. In this respect, the findings imply that students who highly value this learning approach may be subject to issues of mimicry and/or lack of authenticity (i.e., simply following steps of what others did). In the worst case, blind plagiarism may lead to no learning or progression towards threshold concepts at all. The consequences of surface learning have been explored in other studies (Cousin, 2006b; Davies, 2006). Nevertheless, it is still notable that some students adopted a surface learning approach as a virtue of a supportive liminal environment when confronting and dealing with troublesome knowledge. Other studies support surface learning as preliminary stage for building concrete understanding (e.g., Cousin, 2006b; McCartney et al., 2009). Therefore, it is important to help students "learn to live with tensions" and to "value doubt" as central principles of learning (Savin-Baden, 2008b) in a supportive liminal

environment, until they are promoted and become engaged in deeper learning.

Interestingly, *library resources* were found to be the least helpful by the majority of surveyed students. This learning resource was significantly less valued by students in the higher-performance groups. This study did not find evidence of textbooks acting as a barrier to students' learning in GIScience (i.e., the language presented on textbooks may be inaccessible to novice learners). One interpretation is that students may not have made frequent use of textbooks as a learning resource. For example, students often indicated that they rarely used library resources because it was more time-consuming than using other resources.

Although no statistical significance was found, it is still important to note that *online resources*, *discussion with instructors*, and *tutorial instructions/sheets* were more valued by the high-performance group than the low-performance group. It can be interpreted that the high-performance group not only made better use of online resources for detailed information and study, but also more effectively linked their understanding of such material to tutorial instructions under the guidance of instructors. The statistical insignificant relationship may be associated with students' overvaluing of one learning resource over others, ultimately affecting their average ranking score of helpfulness between resources.

#### *Differences between Semester Cohorts*

Crossing thresholds requires students to negotiate and move through liminal spaces (Meyer & Land, 2006b; Savin-Baden, 2008b). Some factors that appeared to hinder this process include pre-liminal variation and lack of motivation/engagement (e.g., Orsini-Jones, 2008), which can affect the ways in which students move through their liminal spaces. Since students' perceptions or attitudes to learning can be shaped or represented by groups of particular characteristics, this study further explored the possibility of significant liminal variations that can occur by semester cohorts. As discussed in Section 4.2.2.4, results from a chi-square test indicated that important student factors for proficiency in GIScience significantly varied between inter-seasonal semesters. The findings indicated that students undertaking the course in Spring terms encountered more difficulty in achieving proficiency in GIS learning, compared to Winter and Fall terms. This suggests that additional effort or support is required for Spring students to pass through their liminal spaces than perhaps compared to other terms.

### 3) *Potential Implications for GIScience in STEM Education*

The last research question addresses, “What are the potential implications for GIScience in STEM education?” This question explored how students moved through their liminal spaces in GIS learning for other STEM-related fields (i.e., concerning post-liminal variation). As detailed in Section 2.5, several studies have considered the theoretical links between GIScience and STEM fields in the context of shared misconceptions (e.g., Bampton, 2012), spatial thinking abilities (e.g., National Research Council, 2006), and academic and career competencies (e.g., Sinton, 2012). More importantly, student interest and success in STEM fields are critical to meeting the increasing demands for a skilled workforce in the community of practice. Therefore, this study has implications not only for the specific course investigated and the Geomatics Program, but also for the University of Waterloo as a whole and the promotion of STEM fields in general.

Students’ disciplinary ways of thinking were found to be dependent on the process of moving through their liminal spaces. As discussed earlier, one factor affecting this process is the students’ prior knowledge and experiences. The findings imply that students from STEM-related fields had stronger quantitative aptitudes, experiences, and capabilities. Due to the nature of the discipline, student backgrounds can be helpful for productively moving through liminal spaces and grasping GIS threshold concepts. As discussed in Section 4.2.2.1, one explanation is that students may have already encountered similar troublesomeness or passed through liminal spaces associated with related knowledge areas. This provides evidence that better foundational training in STEM fields (e.g., similar or related concepts) can also facilitate students’ GIS learning, promoting a distinctive disciplinary way of understanding.

The key aspect of acquiring threshold concepts in GIScience was found to be associated with students’ transformed internal views of the subject matter, particularly with regard to their *geographic* perspective (i.e., ways of looking at a map). There was evidence that post-liminal variation was inherent in students’ ability to think spatially. By assuming that students who acquire threshold concepts are “inside” the subject (Davies, 2006), this study compared students’ average spatial thinking scores based on their performance groups in GIScience. The results indicated that students in the high-performance group (i.e., those who productively moved through liminal spaces) achieved a significantly higher average spatial thinking score than those in the low-performance group. In other words, the higher-performance groups in GIScience were made up of more spatially oriented students. This finding suggests that spatial thinking has become a conceptual foundation for GIScience students and that critical spatial thinking is what occurs in the minds of experienced or competent GIS users. The empirical findings also correspond with those of other studies (e.g., Osmond et al., 2008; Slinger, 2011; Srivastava, 2013; Srivastava &

Tait, 2012). Anderson and Leinhardt (2002) and Downs and Liben (1988) also asserted that understanding how maps represent the surface of the Earth (i.e., being able to see through the map to the real world behind it) is a component of *geographic* expertise shared within the subject's community of practice, which is more difficult for novices to grasp.

Finally, as discussed in Section 4.2.4, another implication of crossing GIScience thresholds is enhancing students' academic and career competencies in other STEM-related fields. Results from a chi-square test indicated that students' current interest in STEM varied significantly between performance groups in the GIScience course. The results showed that students in the higher-performance groups were generally more interested in STEM fields for their academic or career goals than those in lower-performance groups. One interpretation is that proficient GIS learning experiences (i.e., productively crossing the thresholds) can encourage student interest and motivation in STEM education.

To validate this interpretation, students were given written statements and asked to state their level of agreement in order to assess their perspectives on GIS learning experiences. The first statement was whether GIS learning had helped students to develop spatial skills (e.g., visualization, spatial thinking). A chi-square test suggested that students' current interests in STEM varied with whether or not they agreed with this statement. The second statement addressed whether GIS learning had helped develop creativity, critical thinking, and problem-solving skills. A chi-square test also indicated a significant difference. In other words, students interested in pursuing STEM education comprised of those who tended to agree with these statements. Therefore, there was evidence that students' interest and self-confidence in STEM were affected by their GIS learning experiences or vice versa. The findings are consistent with previous studies (e.g., Kerski, 2012; National Research Council, 2006; Newcombe, 2010) that contend that "being able to visualize, analyze, and interpret spatial information is fundamental to content understanding and problem solving, especially in STEM disciplines" (Sinton, 2012, p. 22). Therefore, it is suggested that productively crossing the thresholds in GIScience can enhance students' ability to think spatially, as well as creativity, critical thinking, and problem-solving skills, all of which can help to promote STEM fields.

## **5.2 RESEARCH LIMITATIONS AND FUTURE DIRECTIONS**

It is recognized that this study has certain limitations that may impact or influence the interpretation of the study's findings. For example, the research findings may not be generalized to all introductory GIScience students in higher education, due to the possibility of sample-selection bias. More specifically, the survey population was collected based on a non-random sampling method, *voluntary*

response sampling. Thus, it is possible that the survey population consisted of those who are more interested in the study topic (i.e., more opinionated or contentious students). Students who elected not to participate in the study may have different impressions of GIS learning and thus may be underrepresented in the results due to non-participation. However, this limitation was unavoidable since human participation was voluntary according to research ethics guidelines.

Similarly, since this study's investigation relied on an introductory GIS course at one institution, there may be limitations when generalizing the findings to a broader population. Nevertheless, the large sample size surveyed over multiple years and academic semesters mitigates this bias to a certain extent. It is also notable that "the goal of most qualitative studies is not to generalize but rather to provide a rich, contextualized understanding of some aspect of human experience" (Polit & Beck 2010, p. 1451). Furthermore, sampling from one course enabled us to maximize consistency in terms of the teaching and learning environments (e.g., resources, subject contents, difficulty level) of surveyed students. This consistency was helpful when examining variations in student learning experiences based on their personal and academic characteristics. Nevertheless, the findings could be strengthened and more generalizable if repeated in introductory GIScience courses at other higher education institutions and in different countries and contexts.

Students' levels of knowledge and understanding from prior subject learning were also not examined. This limitation was due to lack of accessibility to students' previous academic records to gauge their performance in prior learning. For example, it is possible that even though students undertook learning in certain subject training/courses, some of them may have failed or performed poorly, while others may have performed extremely well. Instead, it was assumed that students would have successfully passed and achieved the learning outcomes in previous courses before embarking on GIScience learning. If students without a passing grade or course credit (i.e., recognition of prior learning) had been filtered out of the analysis, results regarding important student background factors for proficiency in GIScience may have been different. Future research could consider examining how well students undertook their prior subject learning and comparing this to their performance in GIScience learning.

Another limitation was the study's assumption that surveyed participants would understand the questions and then truthfully and accurately answer them to the best of their abilities. However, students may have been unclear about what was meant by "troublesome" in their learning process. Consequently, some respondents may have guessed when answering questions or else selected choices randomly and/or erroneously. Carstensen and Bernhard (2008) point out that "students may not consider something they have yet to understand as being difficult" (p. 150). Since the survey population was collected at the end

of the academic term but just before the final exam period, it is possible that some students may not have studied all subject materials covered in the course yet. Inevitably, later topics will be less familiar than topics covered at the beginning of the course. Therefore, future work could consider sampling participants after the final exam, although this approach risks acquiring a lower response rate and sample size (i.e., due to the study being undertaken during the exam period). Furthermore, in the survey questionnaire, the ranking of difficulty regarding key concepts was dependent on the concepts selected for comparison. If other concepts were added to the list of potential threshold concepts, the result might have been different. Thus, the troublesomeness of concepts could be assessed based on rating scale questions instead of ranking questions.

The researcher's subjectivity in interpreting qualitative data was another potential limitation of the current study. Cousin (2010) highlighted that "the student experience data becomes the researchers' text to analyze, heightening the risk of the students' experience being represented through the researchers' experience of the students' experience" (p. 7). The interpretation of qualitative data collected from this study relied on only one researcher, which could undermine the reliability and validity of analysis results. However, it is important to note that this study took proactive steps to overcome this limitation. For example, SOLO taxonomy was used as a reference guide during the coding process of the thematic analysis (i.e., for reliability or consistency). A reiteration process was also followed to consolidate the analysis results (i.e., for validity or appropriateness). In future research, this limitation can be further overcome by having additional researchers cross-checking the qualitative data interpretations.

Another limitation of this study pertained to identifying and examining threshold concepts on the basis of their theoretical framework. Other studies also addressed the conceptual and methodological concerns of threshold concepts (e.g., Mead & Gray, 2010; O'Donnell, 2010; Quinlan et al., 2013; Rountree & Rountree, 2009; Rowbottom, 2007). In particular, these studies argue that identification of threshold concepts is not straightforward due to the fairly loose definition that describes their characteristics. For example, the theoretical definition originated by Meyer and Land (2003, 2006) contains some ambiguity or ambiguous words, such as "likely," "probably," and "potentially." Although the definition of threshold concepts has been refined by a series of subsequent studies, this emerging theory is still in its infancy. Consequently, there is still a significant lack of tools and instruments developed or proposed as standard strategies for empirically identifying and analyzing threshold concepts. No consensus exists yet among the research communities on a methodological framework for exploring threshold concepts. Although this study has attempted to combine various techniques widely used in previous studies (e.g., survey questionnaires, personal interviews, concept-mapping), future work could consider developing a

standardized methodological framework for threshold concept research.

Finally, based on the assumption that those who acquire threshold concepts are “inside” the subject (Davies, 2006), this study adopted the standard deviation technique (e.g., Huynh, 2009) to divide students into three performance groups for comparative analysis (i.e., high-, intermediate-, and low-). Students in the high-performance group were assumed to be inside the subject and have successfully crossed thresholds. However, a limitation of this research is that high-performance students were generalized or assumed to have acquired threshold concepts (i.e., successfully moved through liminal spaces) when this might not be the case. Furthermore, mastery of threshold concepts promises to advance students’ levels of competency or understanding in a discipline (i.e., ultimately representing distinctive ways of thinking) (Meyer & Land, 2003; O’Donnell, 2010). However, Rowbottom (2007, p. 263) provides a critique “that concepts are not reducible to abilities ... [and] that acquisition of a given concept can be necessary, but not sufficient, for the progression of an ability.” Rowbottom (2007) goes on to say “that being transformative is arguably an extrinsic property, rather than an intrinsic one” (p. 267). Therefore, “what is a threshold concept for one student may not be a threshold for another” (Ross et al., 2010, p. 47). With this in mind, this study identified and examined the *most prominent* threshold concepts as exploratory examples. However, it did not examine whether these particular concepts were inevitable or sufficient for students’ learning progress in the high-performance group of the discipline. As suggested by Srivastava (2013), further research is needed to examine the actual *effectiveness* of the identified GIScience threshold concepts when applied in practice (e.g., students’ progression of learning). For validation, the first step could involve contemplating the translation of the findings into principles (e.g., curriculum design and development, transactional curriculum). Another possible approach involves developing and conducting focus group interviews to consolidate the study’s empirical findings. This approach can be used to compare and examine how different groups of students might elicit different opinions about the learning experience of particular threshold concepts of interest (i.e., focusing on those most prominently identified). Future research could also delve into examining the threshold concept theory framework in more-advanced GIS courses to monitor how student conceptions change with progressive training.

### **5.3 CONCLUSIONS**

This empirical study investigated a threshold concept framework in GIScience and its potential implications for STEM fields. The research findings are of value particularly to GIScience educators, advisors, researchers, and practitioners, especially in higher education and research institutions.

First, the findings of this study contribute to the threshold concept literature in the field of GIScience (e.g., Srivastava, 2013). In the literature, only a *theoretical* threshold concept framework is discussed based on expert points of view. Therefore, the value of this *empirical* study lies in supplementing current knowledge about this framework in GIScience, based on student insights obtained through survey questionnaires and personal interviews. It was concluded that map projections and data models are the most prominent threshold concepts, acting as conceptual gateways for students' new and previously inaccessible ways of thinking about the central concepts behind mapping. The actual effectiveness of these concepts will need to be further addressed, in relation to student learning progression.

Second, the practical contribution of this research is pedagogically important to curriculum design and development. GIScience is a fairly modern and rapidly growing field, and it is not surprising that GIS learners and practitioners have diversified and expanded. This means that a diversified user base of GIS also has different backgrounds and needs to be addressed when learning GIScience. Findings from this research shed light on ways of helping students or trainees to pass through thresholds and enhance their overall GIS learning process. It is also important to note that, while threshold concepts are suggested to be key focal points of a GIScience course curriculum (i.e., worthy of more emphasis or effort in pedagogical guidance), they are not the only key concepts to cover. GIScience learning should not be over-simplified to a handful of key threshold concepts, since deeper level learning can only be facilitated by a comprehensive and detailed curriculum. In addition, foundational training (e.g., pre-requisite workshops or courses) in other areas of programming, mathematics, or computer science may help students to be better prepared to work through threshold concepts in GIScience.

Finally, the findings have implications not only for the GIScience community, but also for other STEM-related fields in general. This study suggests that productively crossing the thresholds in GIScience can enhance students' spatial thinking abilities, as well as creativity, critical thinking, and problem-solving skills, all of which can help to promote interest and self-confidence when pursuing STEM education. Thus, the growing demands for a skilled and diversified workforce in STEM fields can be fostered by enhanced GIS education.

In conclusion, although the idea of threshold concepts is still in its early stages of development, its potential benefits for teaching and learning should not be overlooked. There are many fields of study and disciplines in which the threshold concepts framework can be potentially and effectively applied. This study offers valuable insight into ways of supporting GIScience learning, which is essential for building a competent workforce of GIS professionals and for shaping its community of learning and practice.

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# APPENDICES

## APPENDIX A – COURSE PATHWAYS OF THE GEOG/PLAN 281 GIS COURSE

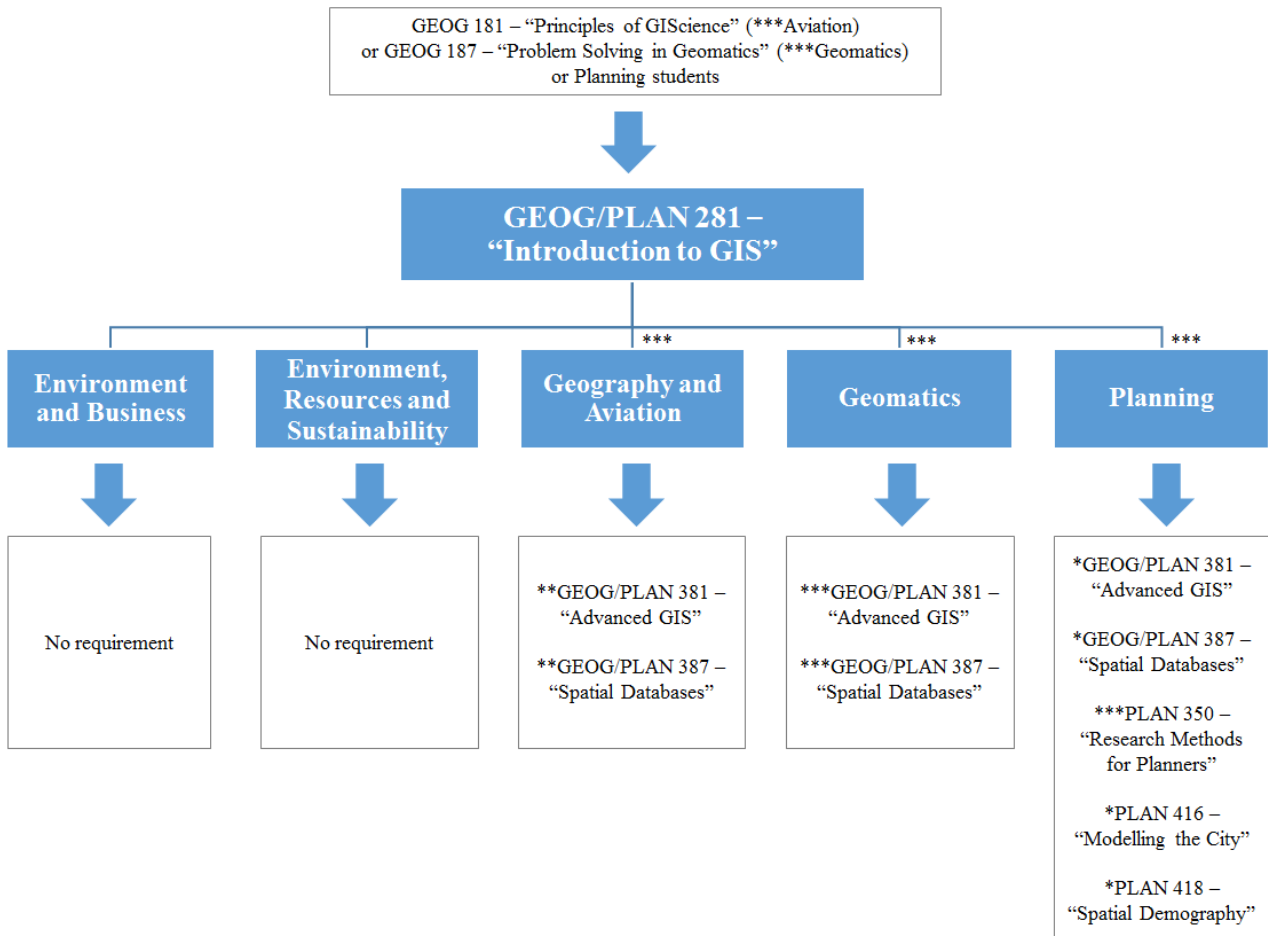


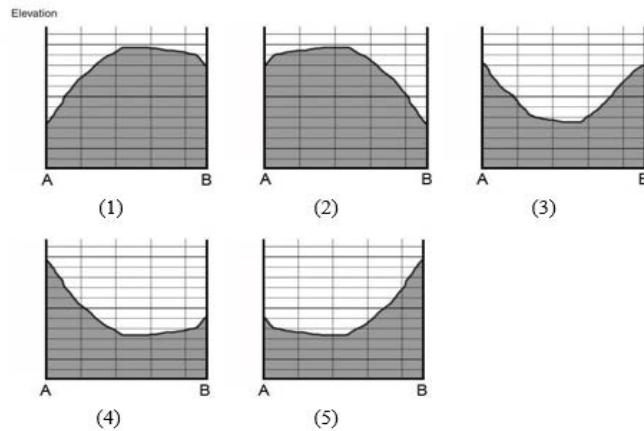
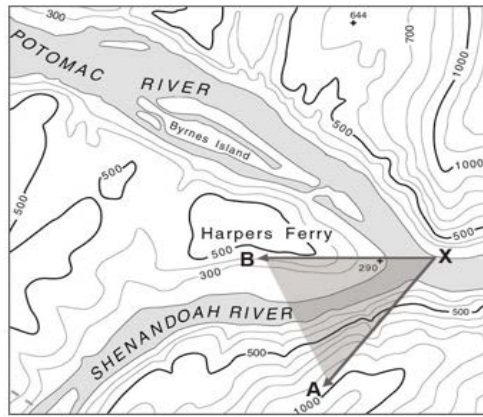
Figure A.1 – A diagram of GEOG/PLAN 281 course pathways as of Spring 2016 (\*Elective, \*\*One of the requirements, \*\*\* Required/compulsory).

*Note.* This course pathway is based on the undergraduate studies academic calendar (Faculty of Environment). More information available at <https://ugradcalendar.uwaterloo.ca/group/uWaterloo-Faculty-of-Environment>

**APPENDIX B – SAMPLE SURVEY QUESTIONNAIRE**

**B.1 SURVEY SECTION 1 – SPATIAL THINKING ABILITY**

**Sample Question 1)** Imagine that you are standing at location X and looking towards the direction of A and B. Which slope profile most closely represents what you would see?



**Sample Question 2)** Which geographic feature below would be most suitable for mapping the Grand River channels and their basins?

- (1) Lines
- (2) Area
- (3) Points and Lines
- (4) Lines and Area

## B.2 SURVEY SECTION 2 – GIS KNOWLEDGE AREAS AND CONCEPTS

**Sample Question 1)** From the GIS-related topics listed below, choose ***three knowledge areas*** that you found were ***the most challenging*** to understand during the GIS learning process.

- Data models (e.g., vector vs. raster)
- Georeferencing (e.g., coordinate systems, datums, map projections)
- Vector data analysis
- Raster data analysis
- Data sources and acquisition
- Data quality (e.g., error, accuracy)
- Spatial data analysis and modelling

**Sample Question 2)** From the ***five concepts*** related to ***Georeferencing*** listed below, **rank** them in order from the easiest (1) to the most difficult (5) concepts to learn.

- Map scale
- Geographic coordinate systems (e.g., longitude, latitude)
- Modelling the Earth (e.g., geoid, ellipsoid, topographic surfaces)
- Map datum (e.g., local, global)
- Map projections

**Sample Question 3)** Answer why you believe that these GIS theories and concepts were perceived as **difficult** or **troublesome** in your learning process. Check all statements below that apply.

- I knew how to create maps (or diagrams) for visual representation using these concepts, but I did not understand the logic behind them, such as the cartographic complexity involved in the representation.
- I understood these concepts but could not understand how they connected with the world around me or to everyday applications.
- I struggled with these concepts, likely due to a mix of misimpressions from everyday experience, mistaken expectations, and complexity of the subject matter.
- What was being taught about these concepts was against my perspective or fundamental point of view (e.g., ethnicity, faith, nationality).
- These concepts were difficult because of the complexity of the knowledge that contained paradoxes, seeming inconsistencies or subtle distinctions in the meaning.
- The terminology or jargon used relating to these concepts was difficult to understand, because it was not familiar to me due to disciplinary backgrounds/training or having different implications and meanings in another discipline.
- None of these statements apply (please specify: \_\_\_\_\_).

### B.3 SURVEY SECTION 3 – GIS SOFTWARE LEARNING FOR CARTOGRAPHY AND VISUALIZATION

**Sample Question 1)** From your own experience, how would you rate the difficulty of ArcGIS as computer software to learn (on a scale of 1 as easy, to 5 as difficult)?

- 1 (easy)
- 2
- 3
- 4
- 5 (difficult)

**Sample Question 2)** Did you find the *visual layout* of ArcGIS software and tools to be a barrier to your software learning process?

- Yes, this was a significant barrier
- Yes, sometimes
- Yes, rarely
- No, never

**Sample Question 3)** Did you find the *terminology* used in ArcGIS to be a barrier to your software learning process (e.g., the terminology of Tools used in ArcToolbox)?

- Yes, this was a significant barrier
- Yes, sometimes
- Yes, rarely
- No, never

#### B.4 SURVEY SECTION 4 – GIS LEARNING RESOURCES

**Sample Question 1)** In terms of tools/materials available for assisting with learning **GIS theories and concepts**, **rank** the following resources in order from ***the most helpful (1) to the least helpful (6)***.

- Lectures and lecture notes
- Tutorials (e.g., Tutorial instructions/sheets)
- Online resources (e.g., LEARN, ArcGIS Help, websites)
- Library resources (e.g., use of books)
- Discussion with peers
- Discussion with instructors (e.g., faculty, TAs, MAD Helpdesk)

**Sample Question 2)** Were ***hands-on lab assignments*** constructive in improving your ***overall learning/comprehension of GIS theories and concepts?***

- Yes, lab assignments helped me to better understand relevant GIS theories and concepts.
- No, they were not helpful to GIS learning.
- Hands-on lab assignments actually impeded my learning of GIS theories and concepts.
- No opinion

## B.5 SURVEY SECTION 5 – ACADEMIC BACKGROUND

**Sample Question 1)** Based on your academic background, how prepared did you feel to undertake GIS learning before enrolling in this class? How would you self-rate your academic preparedness?

- Fully prepared
- Somewhat prepared
- Not prepared

**Sample Question 2)** Which of the following categories *best* describes your academic background before entering this course?

- Quantitative (e.g., physical sciences)
- Qualitative (e.g., arts, social sciences)
- Multidisciplinary (equally both)

**Sample Question 3)** According to your background knowledge and interests, would you classify yourself as any of the following?

- Physical geographer
- Human geographer
- I am not a geographer

**Sample Question 4)** Prior to taking this course, did you have any learning experiences in *physical geography*?

- Yes
- No

B.6 SURVEY SECTION 6 – PERSONAL BACKGROUND

**Sample Question 1)** What is your *gender*?

- Female
- Male

**Sample Question 2)** What is your primary *major of study*?

- Arts
- Aviation
- Computer Science
- Earth and Environmental Sciences
- Environment and Resource Studies
- Engineering
- Environment and Business
- Geography
- Geomatics
- Mathematics
- Planning
- Other (please specify: \_\_\_\_\_)

**Sample Question 3)** What is your current *education status*?

- Undergraduate student – 1<sup>st</sup> year
- Undergraduate student – 2<sup>nd</sup> year
- Undergraduate student – 3<sup>rd</sup> year
- Undergraduate student – 4<sup>th</sup> year
- Undergraduate student – more than 4<sup>th</sup> year
- Others (please specify: \_\_\_\_\_)

B.7 SURVEY SECTION 7 – STEM EDUCATION

**Sample Question 1)** Do you currently have an interest in Science, Technology, Engineering, and Mathematics (STEM)-related disciplines for pursuing your academic or career goals?

- Yes
- No
- Maybe/somewhat

**Sample Question 2)** To what degree do you agree or disagree with the following statement?

*“GIS learning helped to develop my spatial skills (e.g. visualization, spatial thinking), which I believe are important for students’ interest and self-confidence in pursuing successful STEM education and careers.”*

- Strongly disagree
- Disagree
- Maybe/unsure
- Agree
- Strongly agree

**Sample Question 3)** To what degree do you agree or disagree with the following statement?

*“GIS learning helped to develop my creativity, critical thinking, and problem-solving skills, which I believe are important for students’ interest and self-confidence in pursuing successful STEM education and careers.”*

- Strongly disagree
- Disagree
- Maybe/unsure
- Agree
- Strongly agree

**Sample Question 4)** Based on your current GIS knowledge and impression of the discipline, which of the application areas listed below do you think GIS is *potentially the most useful* for? (Limit your selection to *only one* category from below)

- Urban planning/development
- Environmental management
- Emergency/disaster response
- Navigation/transportation
- Agricultural resource management
- Other (please specify in the next question)

B.8 SURVEY SECTION 8 – TRANSFORMATIVE LEARNING EXPERIENCE

**Open-ended Question)** Please specify and explain how understanding certain GIS theories/concepts have (or have not) changed your ways of thinking about GIScience or the world around you. Please indicate any prior knowledge/experience that were helpful in the learning process.

APPENDIX C – KEY GIS KNOWLEDGE AREAS AND CONCEPTS USED IN THE SURVEY

Table C.1 – List of key GIS knowledge areas and concepts used in the survey questionnaire.

Knowledge Areas	Concepts
Spatial data modelling	Definition of a data model; Basic data structure terminology (e.g., field, object data); Differences between vector and raster data structures; Advantages and disadvantages of the vector data model; Advantages and disadvantages of the raster data model
Vector data models	Vector features (points, lines, and polygons); The spaghetti model; The topological model; Relational database management systems
Raster data models	Pixels and grid representation; Grid/cell resolution; Data compression methods (e.g., run length encoding); Scales of measurement of cell values (e.g., nominal, ordinal, interval, ratio)
Georeferencing and map production	Map scale; Geographic coordinate systems (e.g., longitude, latitude); Modelling the Earth (e.g., geoid, ellipsoid, topographic surfaces); Map datum (e.g., local, global); Map projections
Basic spatial data analysis	Geometric measures (e.g., distance, length, shape, area); Query operations; Buffers; Overlay; Map algebra
Vector data analysis	Boolean operators (e.g., AND, OR, NOT); Vector buffers; Vector overlays; Network analysis; Surface modelling (e.g., interpolation, TIN, Thiessen polygons)
Raster data analysis	Raster overlays; Filtering operations; Zonal analysis (e.g., identification, area, perimeter); Raster buffers; Least-cost path analysis
Data sources and acquisition	Primary data sources (e.g., remote sensing, GPS surveys); Secondary data sources (e.g., scanning, digitizing), Metadata, Data editing
Data quality	Scales of measurement of attribute (e.g., nominal, ordinal, interval, ratio); Accuracy vs. precision; Uncertainty and error; Data abstraction (e.g., classification, generalization, exaggeration)

APPENDIX D – HISTOGRAM OF GEOG/PLAN 281 COURSE PERFORMANCE

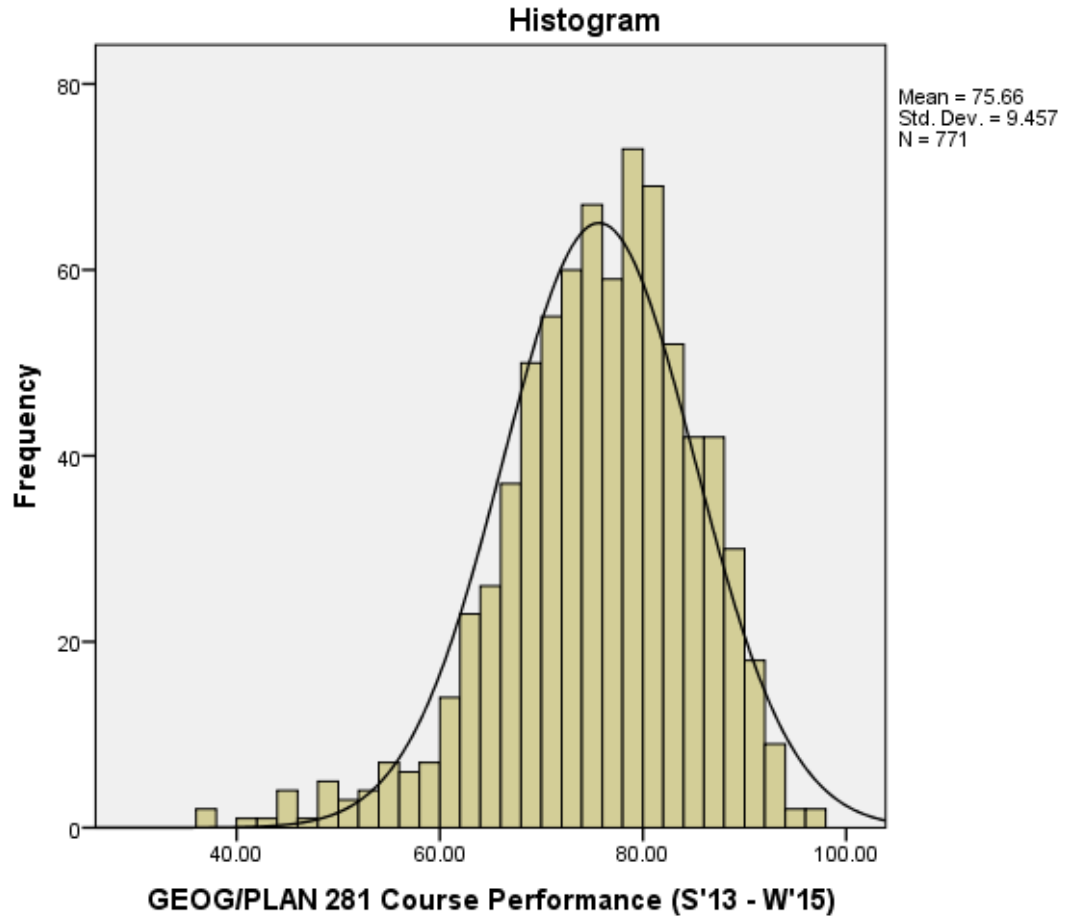


Figure D.1 – Histogram of GEOG/PLAN 281 Course Performance.

## APPENDIX E – PERSONAL INTERVIEW GUIDE TEMPLATE

### ***Goal and Objectives***

The main goal of this personal interview is to explore individual students' self-reflection on their transformative episodes of learning in GIScience. More specifically, the objectives are as follows:

- To examine which bottleneck candidates (concepts found to be challenging in GEOG/PLAN 281 – Introduction to GIS) were prominently evident in students' transformative learning experiences, and how these concepts changed their ways of thinking about the subject matter;
- To assess the roles of student characteristics and other fundamental concepts on students' understanding of potential threshold concept(s); and
- To explore students' learning approaches (e.g., resources) used to overcome barriers to learning (i.e., for crossing thresholds).

*Beginning the interview, the study purpose and background were introduced to the individual participants. The overall structure of the interview was then encapsulated.*

### ***Section 1: Critical Concepts in GIScience***

- 1.1 Provide red index cards representing potential threshold concept (bottleneck) candidates that GIScience students often find challenging. As a screening process, ask participants to select all the concepts that they perceive as critical to competency in the GIScience community (i.e., the ways of thinking and practising distinctive to GIScience).
- 1.2 Remove the unselected concepts.
- 1.3 Allow participants to explain why they selected the concepts.

### ***Section 2: Concept-mapping Exercise***

- 2.1 Ask participants to place and arrange the selected concepts on the whiteboard and create a concept map by drawing lines (red) between the concepts that complemented each other and thus enhanced the process of learning.
- 2.2 Allow participants to explain how these concepts were related or complemented each other.

### ***Section 3: Evidence of Threshold Concepts***

- 3.1 Ask participants to circle the concepts which, once understood, changed their ways of thinking about the subject matter. If participants argue that there were no such concepts that transformed their ways of thinking, then the rest of the interview focuses on exploring how their backgrounds and learning approaches (next section) were or were not helpful for the critical concept(s) that they indicated in previous.

- 3.2 Ask participants how the circled threshold concept(s) made them appreciate the GIS application area (e.g., urban planning, environmental management, transportation) in the world around them.
- 3.3 Ask participants how the threshold concept(s) changed their ways of thinking in academic (e.g., subject matter, study major) and career (e.g., goals, capability) perspectives.
- 3.4 Ask participants how understanding the threshold concept(s) helped enhance their understanding of other connected concepts on the concept map (i.e., capturing any information that they might have missed during their thought process in Step 2.2).
- 3.5 Ask participants to share any troublesome learning experience of the threshold concept(s).
- 3.6 Remove the concepts that were not circled, leaving only the threshold concept(s) on the whiteboard.

#### ***Section 4: Student Backgrounds***

- 4.1 Ask participants how learning the threshold concept(s) was affected by their backgrounds (if any): academic preparedness, educational status, study major, academic background type, and prior subject learning experience.
- 4.2 Provide blue index cards representing additional concepts (e.g., potential building blocks for transformative learning) taught in GEOG/PLAN 281. Ask participants to select the ones that facilitated progress in learning the threshold concept(s) identified in Step 3.1.
- 4.3 Ask participants to arrange the selected ones on the whiteboard and add them to the concept map by drawing lines (blue) to the identified threshold concept(s). Let participants explain how these selected building blocks were helpful for learning the connected threshold concept(s) one by one.
- 4.4 Provide empty blue index cards on which participants can write down any additional concepts that acted as building blocks (i.e., from the same subject matter or any other disciplines). Again, follow the same procedure in Step 4.3.

#### ***Section 5: GIS Learning Approaches***

- 5.1 Ask participants how the experience of GIS software affected learning the threshold concept(s).
- 5.2 Provide index cards of learning resources of GIS theory and concepts that are available for the course. Ask participants to rank them in the order that they found most useful for learning the threshold concept(s). Let participants explain how they were or were not helpful.
- 5.3 Provide index cards of deep and surface learning style examples. Ask participants to rank them in the order that they found most preferable/applicable for learning the threshold concept(s). Let participants explain how they were or were not helpful.

*When wrapping up the interview, ask participants for general comments/feedback regarding the identified threshold concepts or the overall GIS learning experience.*

## APPENDIX F – ETHICS MATERIALS

### F.1 RECRUITMENT LETTER (WED-BASED SURVEY QUESTIONNAIRE)

Dear GEOG/PLAN 281 Students:

My name is Bill Hamm, an MSc student working under the supervision of Dr. Su-Yin Tan in the Department of Geography and Environmental Management at the University of Waterloo. You are invited to participate in a research study through the end-of-term GEOG/PLAN 281 GIS Education User Questionnaire.

The objective of this questionnaire is to identify key barriers/troublesome knowledge in GIScience, as well as to provide insight into the overall process of learning GIScience-related skills and concepts. The survey is also intended to gauge your spatial thinking abilities and your perspectives in Science, Technology, Engineering, and Mathematics (STEM).

Your responses will help to better inform GIS teaching and learning strategies, not only in this course and the Geomatics Program, but also at the University of Waterloo and beyond.

Participation in this survey is voluntary, and there are no known or anticipated risks. The survey is not a course requirement or a course evaluation. The questionnaire is to be completed anonymously – student IDs or names will not be recorded in the survey database. The course instructor will not be informed of who did or did not participate in the study until after final course grades have been submitted.

This study has been reviewed and received ethics clearance through the University of Waterloo Research Ethics Committee. However, the final decision about participation is yours.

The survey will be available for 10 days. Access will terminate at [TIME] on [DATE]. The survey can be accessed via LEARN (Assessments > Surveys). More information about the survey and complete instructions are available on the first page of the LEARN online survey.

If you have any questions about this study, or would like additional information to assist you in reaching a decision about participation, please feel free to contact me.

Sincerely,

Bill Hamm  
sbhamm@uwaterloo.ca

## F.2 INFORMATION LETTER AND CONSENT FORM (WEB-BASED SURVEY QUESTIONNAIRE)

### **GIS Education User Questionnaire GEOG/PLAN 281**

The purpose of this end-of-term GEOG/PLAN 281 GIS Education User Questionnaire is to identify key barriers/troublesome knowledge in GIScience, as well as to provide insight into the overall process of learning GIScience-related skills and concepts. The survey is also intended to gauge your spatial thinking abilities and your perspectives on Science, Technology, Engineering, and Mathematics (STEM) education.

Your responses will help to better inform GIS teaching and learning strategies, not only in this course and the Geomatics Program, but also at the University of Waterloo and beyond.

The findings from this survey will be reported for quality assurance, as well as be part of a research study by Dr. Su-Yin Tan and Bill Hamm (Department of Geography & Environmental Management) about GIS education at the University of Waterloo. All information you provide is completely confidential. The questionnaire is completed anonymously – student IDs or names will not be recorded in the final survey database, and any quotations used will be anonymous. A graduate teaching assistant will process survey results, and the course instructor will not be informed of who did or did not participate in the study until after final course grades have been submitted.

This study has been reviewed and received ethics clearance through the University of Waterloo Research Ethics Committee. If you have any comments or concerns resulting from your participation, please contact Dr. Maureen Nummelin in the Office of Research Ethics at 519-888-4567, Ext. 36005 or e-mail at maureen.nummelin@uwaterloo.ca.

- This survey consists of eight sections and should take you about 20-30 minutes to complete.
- Please answer all questions to the best of your ability based on your own GIS learning experience. Your responses will not be judged in terms of your current performance/standing in the course.
- Please read and follow instructions carefully and provide constructive comments where indicated.
- This survey questionnaire is NOT a course evaluation of GEOG/PLAN 281.

Click 'Next Page' to participate in the survey and proceed to the next section. Make sure to click 'Submit' once you have completed the questionnaire. You will be able to submit your responses only once.

#### **IMPORTANT NOTES:**

*The survey will be available for 10 days. Access will terminate at [TIME] on [DATE].*

#### **Consent to Participate**

- I agree to participate (Click "Next Page")
- I do not wish to participate (please close your web browser now)

F.3 FEEDBACK/APPRECIATION LETTER (WEB-BASED SURVEY QUESTIONNAIRE)

***FINAL STEP:***

***Please click the "Submit" button below.***

***Thank you for completing this questionnaire!***

Your feedback is extremely valuable. If you are interested in viewing the results of this survey or have any general comments or questions related to this study, please contact Bill Hamm or Dr. Su-Yin Tan (contact information provided below).

We would like to assure you that this study has been reviewed by, and received ethics clearance through the University of Waterloo Research Ethics Committee. If you have any concerns regarding your participation in this study, please contact Dr. Maureen Nummelin, the Director, Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Contact information:

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Tel: +1-519-888-4567, ext. 38772  
Office: EV1-103A  
Department of Geography & Environmental Management  
200 University Ave. West, Waterloo, Ontario, Canada, N2L 3G1

Bill Hamm  
E-mail: sbhamm@uwaterloo.ca  
Department of Geography and Environmental Management

#### F.4 RECRUITMENT LETTER (INTERVIEW)

Subject Line: Interview Participation for GIS User Questionnaire (Invitation)

Dear GEOG/PLAN 281 Students,

My name is Bill Hamm, an MSc student working under the supervision of Dr. Su-Yin Tan in the Department of Geography and Environmental Management at the University of Waterloo.

This e-mail is an invitation to consider participating in a GIS education research study which will involve a semi-structured interview (approximately 20-30 minutes) based on the GIS Education User Questionnaire. For your participation, FREE refreshments (e.g., samosas, donuts, coffee) will be provided after the interview.

This interview is an opportunity to provide your insight into the overall process of learning GIScience-related skills and concepts. Your responses will help to better inform GIS teaching and learning strategies, not only in this course and the Geomatics Program, but also at the University of Waterloo and beyond.

I would like to assure you that the study has been reviewed and has received ethics clearance through the University of Waterloo Research Ethics Committee.

If you are interested in participating, please book your appointment through the following link as soon as possible: **[gp281interview.youcanbook.me](http://gp281interview.youcanbook.me)**

Once the booking is made, I will send a confirmation e-mail indicating that you have been signed up and a reminder e-mail before the interview. The interview will take place in *[LOCATION]* from *[DATE]* to *[DATE]*.

If you have any questions, please feel free to contact me at [sbhamm@uwaterloo.ca](mailto:sbhamm@uwaterloo.ca) or Dr. Su-Yin Tan at [su-yin.tan@uwaterloo.ca](mailto:su-yin.tan@uwaterloo.ca).

Sincerely,

Bill Hamm  
[sbhamm@uwaterloo.ca](mailto:sbhamm@uwaterloo.ca)

## F.5 INFORMATION LETTER AND CONSENT FORM (INTERVIEW)

University of Waterloo

Date

Dear (*participant's name*),

This letter is an invitation to consider participating in a GIS education research study, which will involve a semi-structured interview (approximately 20-30 minutes) based on the GIS Education User Questionnaire. For your participation, FREE refreshments (e.g., samosas, donuts, and coffee) will be provided after the interview.

This interview is an opportunity to provide your insight into the overall process of learning GIScience-related skills and concepts. Your responses will help to better inform GIS teaching and learning strategies, not only in this course and the Geomatics Program, but also at the University of Waterloo and beyond.

With your permission, the interview will be audio recorded to facilitate collection of information, and later transcribed for analysis. All information you provide will be considered confidential. Your name will not appear in any thesis or report resulting from this study. The information collected from this session will be kept in a secure and password protected computer in a locked office in my supervisor's lab in the Department of Geography and Environmental Management. Participation in this study is voluntary, and there are no known or anticipated risks.

If you have any questions regarding this study, please feel free to contact me (sbhamm@uwaterloo.ca) or Dr. Su-Yin Tan (su-yin.tan@uwaterloo.ca).

This study has been reviewed and has received ethics clearance through the University of Waterloo Research Ethics Committee. If you have any comments or concerns resulting from your participation, please contact Dr. Maureen Nummelin in the Office of Research Ethics at 519-888-4567, Ext. 36005 or e-mail at maureen.nummelin@uwaterloo.ca.

Sincerely,

Bill Hamm  
sbhamm@uwaterloo.ca

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**CONSENT FORM**

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

---

I have read the information presented in the information letter about a study being conducted by the student investigator, Bill Hamm, in the Department of Geography and Environmental Management at the University of Waterloo. I have had the opportunity to ask any questions related to this study and any additional details I wanted.

I am aware that I have the option of allowing my interview to be audio recorded to ensure an accurate recording of my responses.

I am also aware that excerpts from the interview may be included in the thesis and/or publications to come from this research, with the understanding that the quotations will be anonymous.

I was informed that I may withdraw my consent at any time by informing the facilitator.

This project has been reviewed by, and received ethics clearance through the University of Waterloo Research Ethics Committee. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director of Office of Research Ethics at 519-888-4567 ext. 36005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

YES       NO

I agree to have the interview audio recorded.

YES       NO

I agree to the use of anonymous quotations in thesis or publications that comes of this research.

YES       NO

---

Participant Name

---

Participant Signature

---

Date

## F.6 FEEDBACK/APPRECIATION LETTER (INTERVIEW)

University of Waterloo

Date

Dear (*participant's name*),

I would like to thank you for your participation in the GIS education research study. As a reminder, the purpose of this study is to better understand students' insight into the overall GIS learning process.

The data collected during the interview will help to better inform GIS teaching and learning strategies. Please remember that any data pertaining to you, as an individual participant, will be kept confidential.

As with all University of Waterloo projects involving human participants, this project was reviewed by, and received ethics clearance through, the University of Waterloo Research Ethics Committee. Should you have any comments or concerns resulting from your participation, please contact Dr. Maureen Nummelin, the Director of Office of Research Ethics, at 1-519-888-4567, Ext. 36005 or [maureen.nummelin@uwaterloo.ca](mailto:maureen.nummelin@uwaterloo.ca).

Upon your request, I will be happy to share the results when the research work is completed. If you also have any further questions or want to know more about the study, please do not hesitate to contact me.

Once again, I appreciate your participation, and it was a pleasure to meet you.

Sincerely,

Bill Hamm  
[sbhamm@uwaterloo.ca](mailto:sbhamm@uwaterloo.ca)

## APPENDIX G – INTERVIEW ROOM AND EQUIPMENT



Figure G.1 – The interview room setting.

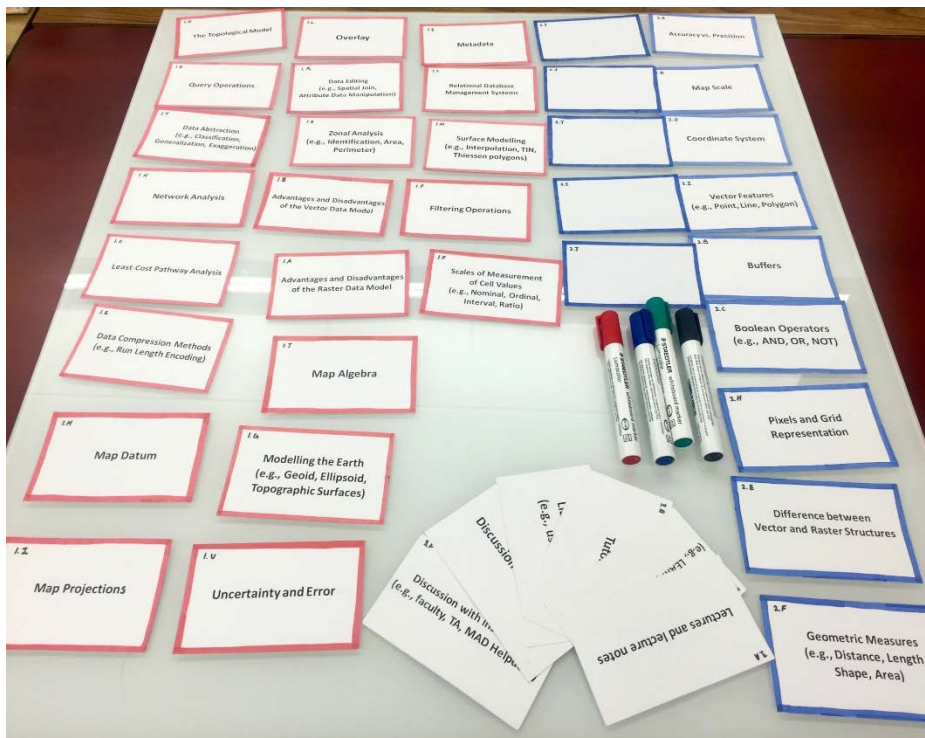


Figure G.2 – The interview equipment.

APPENDIX H – THEMES AND CODING CATEGORIES FOR THEMATIC ANALYSIS

Table H.1 – Themes and coding categories used for thematic analysis of qualitative data.

ID	Themes	Coding Categories
Theme #1	Transformative learning experience	Yes
		No
		Yes (did not specify threshold concepts)
		Advantages and disadvantages of raster data model
		Advantages and disadvantages of vector data model
		Map algebra
		Query operations
		Overlay
		Least-cost path analysis
		Filtering operations
Theme #2	Potential threshold concepts	Modelling the Earth (e.g., geoid, ellipsoid, topographic surfaces)
		Map datum (e.g., local, global)
		Map projections
		Metadata
		Data editing
		Uncertainty and error
		Data abstraction (e.g., classification, generalization, exaggeration)
		Surface modelling (e.g., interpolation, TIN, Thiessen polygons)
		Network analysis
		Relational database management systems
Theme #3	Potential building blocks	The topological model
		Data compression methods (e.g., run length encoding)
		Scales of measurement of cell values (e.g., nominal, ordinal, interval, ratio)
		Accuracy vs. precision
		Buffers
		Boolean operators (e.g., And, Or, Not)
		Coordinate system
		Difference between vector and raster structures
		Geometric measures (e.g., distance, length, shape, area)
		Map scale
Theme #4	The role of student backgrounds	Pixels and grid representation
		Vector features (points, lines, polygons)
		Other
		Prior learning experience
Theme #5	GIS software experience	Prior career or co-op experience
		Major field of study
		Everyday life experience
Theme #6	Learning resources	Facilitated learning GIScience
		Impeded learning GIScience
		Lectures and lecture notes
		Tutorials (e.g., tutorial instructions/sheets)
		Online resources (e.g., ArcGIS Help)
Theme #7	Learning styles	Discussion with peers
		Discussion with instructors
Theme #8	Implications for STEM	Library resources (e.g., books)
		Surface learning
		Deep learning
Theme #8	Implications for STEM	Geographical/critical thinking
		Academic and career competencies

APPENDIX I – ASSESSMENT OF THRESHOLD CONCEPTS USING THE SOLO TAXONOMY

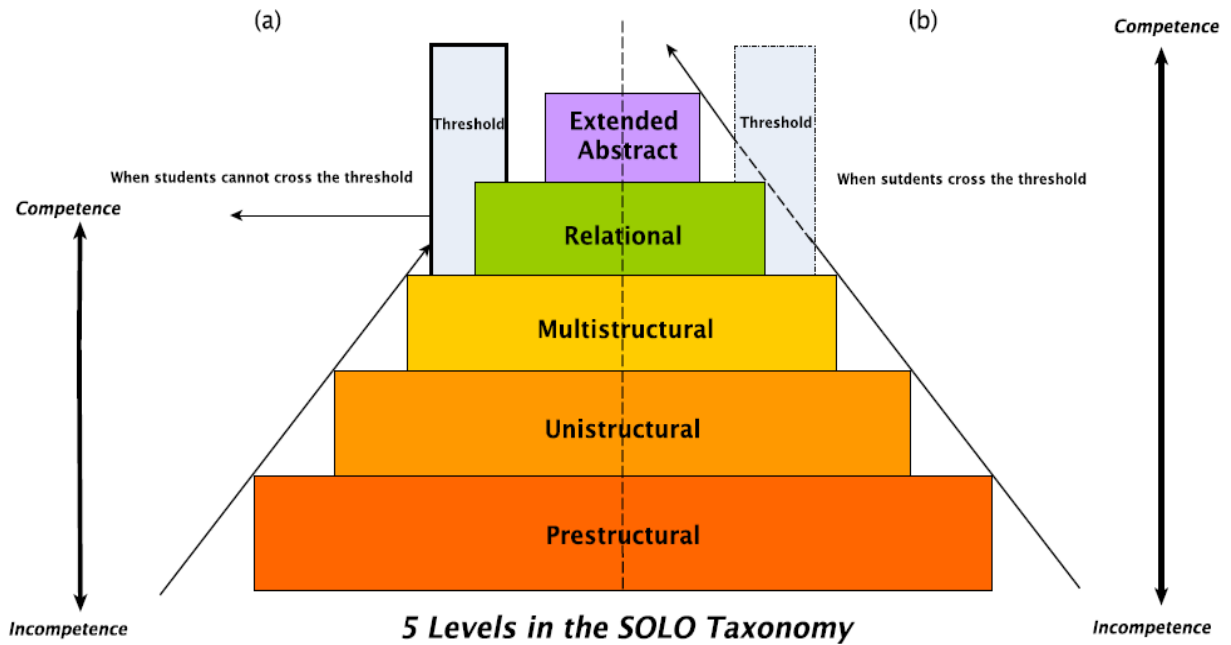


Figure I.1 – A visual representation of the acquisition of a threshold concept with respect to the levels of learning outcomes in the SOLO taxonomy: (a) when students cannot cross the threshold and (b) when students cross the threshold.