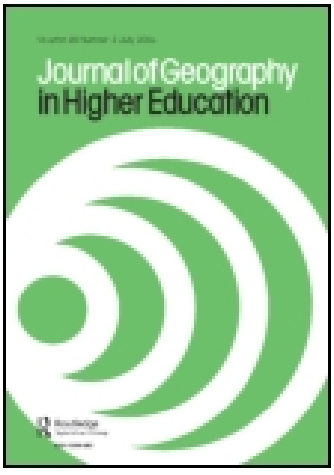

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Twenty-four pre-service teachers participated in a workshop designed to provide explicit opportunities to learn what spatial thinking is and how to incorporate it into teaching practice. The objectives of this paper are to: (1) examine the educational effect of the workshop on pre-service teachers' pedagogical content knowledge (PCK) and (2) provide geographers who prepare teachers in higher education with insights into effective ways to address PCK to teach spatial thinking in teacher preparation programs. The findings of this study indicate that explicit instruction in teaching spatial thinking is necessary and effective to develop pre-service teachers' PCK.

Keywords: spatial thinking; pedagogical content knowledge; pre-service teachers; teacher education

Introduction

Spatial thinking has been defined in many ways, but one of the most compelling and comprehensive definitions is presented in a publication *Learning to Think Spatially*, where it is characterized as "a collection of cognitive skills comprised of knowing concepts of space, using tools of representation, and reasoning processes" (National Research Council, 2006, p. 12). Concepts of space, the first component, are the building blocks of spatial thinking. Spatial concepts help learners obtain, understand, and communicate knowledge about space effectively and efficiently. Representations such as maps, models, diagrams, and graphs, the second component, serve as tools to facilitate spatial thinking by stimulating complex reasoning (Newcombe & Huttenlocher, 2000; Uttal, 2000) and organizing and externalizing abstract information into more understandable and, therefore, easily communicable forms (Mathewson, 1999; Tversky, 2005). Reasoning processes, the third component of spatial thinking, enable knowledge about space and representations to be combined for decision-making and problem-solving through analysis, hypothesis-making, generalization, and evaluation (National Research Council, 2006).

Proficiency in spatial thinking is associated with success in many disciplines, such as engineering, architecture, medicine, mathematics, and sciences including geography (Hegarty, 2010; Hespanha, Goodchild, & Janelle, 2009; LeGates, 2009; Liben, 2006; Newcombe, 2010; Shea, Lubinski, & Benbow, 2001). The National Research Council study makes the case that spatial thinking is one of the important forms of thinking that should be taught in schools. Despite growing interest in the development of students' spatial thinking, termed spatial literacy, it is not yet a systematic and integral part of

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education in the USA (Bednarz, Stoltman, & Lee, 2004; Liben & Downs, 2003; National Research Council, 2006), let alone in geography classrooms. Research is emerging on the types of courses (e.g., Lee & Bednarz, 2009), classroom activities (e.g., Hooey & Bailey, 2005), and technologies (e.g., Bodzin, 2011; Milson & Curtis, 2009) that can support students' spatial thinking, but few studies inform effective ways to prepare teachers to be able to teach spatial thinking in their future classrooms. A recent nationwide study on the status of geography education in the USA, *A Road Map for 21st Century Geography Education*, stresses that enhancing pre-service teacher education programs is necessary to "maximize geographic literacy for all students" (Schell, Roth, & Mohan, 2013, p. 92). The study identifies teachers' content knowledge and pedagogical content knowledge (PCK) as "two core types of knowledge" that teacher professional development programs focus to develop (Schell et al., 2013, p. 76) and calls for more research on how teachers develop such knowledge (Bednarz, Heffron, & Huynh, 2013; Schell et al., 2013). This paper addresses such research needs with two specific objectives: (1) to examine the effectiveness of an educational intervention we term a *workshop* designed to develop pre-service teachers' PCK for teaching spatial thinking through geography and (2) to provide geographers who prepare teachers in higher education with insights into effective ways to address PCK to teach spatial thinking in teacher preparation programs.

Defining PCK to teach spatial thinking through geography

The importance of PCK in accounting for effective teaching has long been recognized in education literature (e.g., Alonzo, Kobarg, & Seidel, 2012; Brophy, 1991; Carlsen, 1999; Guyver & Nichol, 2004; Kleickmann et al., 2013; Phelps & Schilling, 2004). Nevertheless, characteristics of teachers' PCK that can support students' learning to think spatially are not yet understood, and little research exists that helps envision a teacher's PCK for teaching spatial thinking in geography classrooms. Shulman defined PCK as a "special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987, p. 8). PCK is knowledge about the best way to teach subject matter, and it is about "the ways of representing and formulating a subject that makes it comprehensible to others" (Shulman, 1986, p. 9). Thus, PCK for teaching spatial thinking through geography can be defined as the teachers' ability to represent geographic concepts and ideas in a way to promote students' spatial thinking skills. Teachers possessing such PCK should be able to incorporate the ideas of spatial thinking and its three key components – concepts of space, tools of representation, and processes of reasoning – into a variety of teaching practices including planning a lesson and designing assessment items. This definition implies that teachers' knowledge and understandings of the nature of spatial thinking and its key components, significance of spatial thinking in a variety of contexts, and spatial concepts and perspectives in geography are prerequisite to the development of PCK to integrate spatial thinking into classrooms.

Building PCK to teach spatial thinking through geography

Teacher preparation in geography should play an important role in building such knowledge (Darling-Hammond, Holtzman, Gatlin, & Heilig, 2005; Doppen, 2007; Franklin & Molebash, 2007; Schell et al., 2013). Despite the wide variation in teacher preparation, called "pre-service education" in the USA, and certification systems, most teacher preparation in geography takes place under the domain of social studies, of which

geography is a strand (Bednarz & Bednarz, 1995; Bednarz et al., 2004). In many states, social studies teacher preparation focuses primarily on history, and geography coursework is seldom required. A result is that most classroom teachers teaching geography have little or no formal preparation in the subject (Bednarz & Bednarz, 1995; Bednarz et al., 2004; Boehm, Brierley, & Sharma, 1994). Even if teachers took an introductory geography course as a part of their college education or teacher preparation coursework, such classes may not be readily translated into useful knowledge and skills in a classroom (Gregg, 2001). It is, therefore, unlikely that pre-service teachers acquire PCK for effective teaching of geography. Especially for teaching new or unfamiliar topics such as spatial thinking, "preservice teachers are among the educators most in need of preparing themselves to teach new topics" (Gregg, 2001, p. 61).

Research on teacher education indicates that the degree to which a teacher integrates new ideas and techniques in practice depends largely on the teacher's interpretation of the value of these ideas and techniques for supporting teaching and learning (Hughes, 2005). Developing PCK also requires teachers to practice creating "multiple examples, memorable analogies, images, and representations of challenging topics" as well as to build "their repertoire of strategies, practices, and representations for making geography understandable" (Schell et al., 2013, p. 78). Binko (1989) argues that the level of skill and confidence that teachers need to effectively implement new ideas in their own classrooms can be achieved only when they have sufficient opportunities to practice the skills to which they have been introduced. Therefore, it seems evident that developing PCK to teach spatial thinking through geography requires pre-service teachers to have explicit opportunities to learn about spatial thinking, with a special emphasis on its significance and relevance to a broad learning context, and to practice incorporating it into a variety of teaching milieus.

Methods

Workshop: Teaching Spatial Thinking Through Geography

Based on the insights learned from the literature, a one-day, approximately four-hour training workshop – *Teaching Spatial Thinking Through Geography* – was developed to assist prospective teachers in making meaningful connections between the idea of spatial thinking and teaching of geography. The first session of the workshop dealt with basic yet fundamental information about spatial thinking, such as its definition, three component parts, and its significance. This session also explicitly discussed important spatial concepts in geography (e.g., location, region, pattern, diffusion, and overlay) that teachers and students should know. Focusing on strategies to incorporate spatial thinking into practice, the second and third sessions intended to help participants visualize the "teachability" (Shulman, 1986, p. 9) of spatial thinking in their future classrooms. They watched a video of an exemplary geography lesson and evaluated it in terms of the three components of spatial thinking. In the last session, participants examined six geography-focused questions sampled from the exit level social studies Texas Assessment of Knowledge and Skills test, analyzed them from a spatial perspective, and shared their ideas and opinions on how the test items could be revised to stimulate students' practice of spatial thinking.

Throughout the workshop, a taxonomy of spatial thinking developed by Jo and Bednarz (2009) was used as a tool to support students' systematic incorporation of spatial thinking into teaching practice. This taxonomy was considered to be an effective learning tool for pre-service teachers because it features the three components of spatial thinking – concepts of space, tools of representation, and reasoning processes – explicitly in its three-

dimensional structure. During the first session of the workshop, the taxonomy helped participants conceptualize spatial thinking and better understand its key components. A detailed explanation on the subcategories of each component assisted pre-service teachers to recognize varying levels of abstractedness and complexity of concepts (i.e., spatial primitives, simple-spatial, and complex-spatial) and cognitive processes (i.e., input, processing, and output) involved in spatial thinking. As pre-service teachers came to understand that each of the 24 cells of the taxonomy represents a unique combination of the subcategories of the three components of spatial thinking, they were able to examine teaching and learning materials and activities from a spatial perspective. Using examples accompanying the taxonomy, participants practiced selecting, evaluating, and designing spatially rich geography lessons and assessment items.

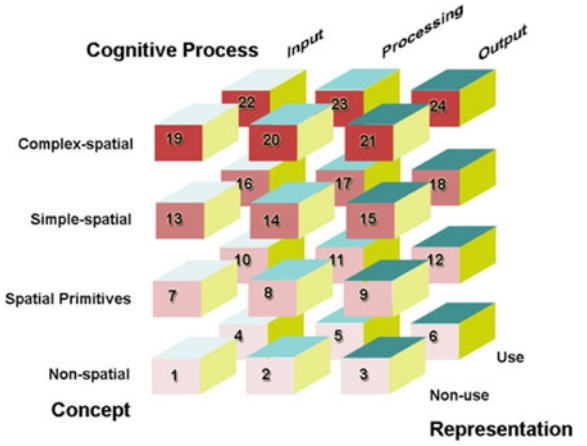
Participants

Twenty-four undergraduate students participated in this study. The participants were all seeking elementary or middle school teacher certification. Twenty-one participants were female, and three were male. The average number of courses in geography taken by participants was 1.6, mostly in introductory human geography, world regional geography, or introductory physical geography. The average number of education courses taken was 6.6 including a social studies teaching methods course.

Assessment of PCK

Lesson plans were considered to be a valid indicator of a teacher's PCK as they reflect the teacher's ability to formulate appropriate learning objectives, to design and employ effective classroom activities, and to ask questions that can facilitate students' thinking. Participants of this study were asked to create lesson plans on a given topic before and after the workshop. Brief instruction in the purposes and main components of a lesson plan were provided, and a copy of a high school level world geography textbook chapter about settlement patterns and ways of life in Canada was given as the material to work with. Participants read through the text individually and had a group discussion to share information about the material. Then approximately 40 minutes was given to work on an individual lesson plan. Participants were asked to include in their lesson plans: (1) three lesson objectives, (2) step-by-step instructional procedures, such as students' and the teacher activities, and (3) three assessment questions or tasks. A lesson-plan template was provided to keep the format of the lesson plans consistent.

The spatiality of participant-produced lesson plans was evaluated based on the degree to which the lesson plan addresses three components of spatial thinking in an explicit manner. Using the taxonomy of spatial thinking (Figure 1), each of the lesson objectives and assessment items was coded by: (1) classifying the concepts that the objective (or assessment item) required students to know (i.e., non-spatial, spatial primitives, simple-spatial, complex-spatial concepts), (2) determining the nature of the tools of representation that the objective (or assessment item) asked students to use (i.e., non-use, use), and (3) classifying the cognitive processes that each objective (or assessment item) expected to address (i.e., input, processing, output level). Examples of coding are illustrated in Table 1. The second example is an assessment item asking students to name and describe five regions of Canada. The concept students are expected to know to answer the question is "region," a simple-spatial concept. Students were neither provided with a representation nor directed to use one from textbook or other sources, so this question should be coded



Representation

Non-use	Use
	Maps
	Diagrams
	Charts
	Graphs
	Images

Concept

Non-spatial	Spatial primitives	Simple-spatial		Complex-spatial	
	Location	Distance	Shape	Distribution	Gradient
	Place-identity	Direction	Boundary	Pattern	Profile
	Magnitude	Connection	Region	Dispersion	Relief
		Movement	Arrangement	Clustering	Scale
		Transition	Adjacency	Density	Map projection
		Reference frame	Enclosure	Diffusion	Buffer
				Dominance	Overlay
				Hierarchy	Spatial association
				Network	

Cognitive process

Input		Processing		Output	
Name	Observe	Explain	Organize	Evaluate	Create
Define	Describe	Analyze	Sequence	Judge	Design
List	Select	State causality	Summarize	Predict	Invent
Identify	Complete	Compare	Synthesize	Forecast	Imagine
Recognize	Count	Contrast	Infer	Hypothesize	Generalize
Recite	Match	Classify	Make analogies	Speculate	Build a model
Recall		Categorize	Experiment	Plan	Apply a principle

Figure 1. A taxonomy of spatial thinking. *Source*: Modified from Jo and Bednarz 2009.

Table 1. Example coding of lesson objectives and assessment items.

Example lesson objectives and assessment items	Concept	Using tools of representation	Processes of reasoning
To explain why they believe Canada is a plural society	Non-spatial	Non-use	Processing
Name and describe each of Canada's regions	Simple-spatial	Non-use	Input
To explain patterns of settlement due to climate conditions through class discussion and evaluation of maps	Complex-spatial	Use	Processing

"non-use of representation." It is at the input level in terms of the cognitive processes because the question requires only recalling the names and characteristics of each region of Canada. Descriptive statistic methods, such as frequencies and percentages, were used to analyze and summarize the results.

The teaching and learning procedures component of the lesson plans and interview transcripts were analyzed qualitatively, using the constant comparative method. In this method, the categories of units are likely to emerge as data coding proceeds, and the constant comparison of a unit with the other units leads to the development of categories (Lincoln & Guba, 1985). The analysis on teaching and learning procedures focused on the differences between pre- and post-lesson plans. To verify whether the changes participants made in their post-lesson plans reflected their effort to incorporate the three components of spatial thinking, a face-to-face interview was conducted with each participant, and participants were asked to explain their rationales for revising the lesson plans.

Results and discussion

Findings from a quantitative analysis: spatiality of lesson objectives and assessment items

A total of 71 lesson objectives and 71 assessment items from pre-lesson plans, and 71 lesson objectives and 74 assessment items from post-lesson plans were created by the participants and analyzed quantitatively. The spatiality of pre- and post-lesson objectives and assessment items was compared in terms of: (1) the frequency of spatial concepts featured at different levels, (2) the number of spatial representations used, and (3) the amount of low- and high-level cognitive processes involved (Figure 2).

For the lesson objectives (left column), more complex-spatial concepts, such as pattern and distribution, appeared in the post-lesson plans (26.76%) than in the pre-lesson plans (15.49%). Post-lesson plans also included relatively more objectives related to using tools of representation (30.99%) than pre-lesson plans did (22.54%). It was also observed that the number of objectives addressing input-level thinking decreased from pre- (40.85%) to post-lesson plans (25.35%), whereas those demanding processing- and output-level cognition increased (from 49.30% to 57.75% and from 9.85% to 16.90%, respectively). Overall spatiality of the participant-designed assessment items (right column) also improved in post-lesson plans. More items requiring simple- and complex-spatial concepts appeared in the post-lesson plans (from 43.66% to 50.00% and from 11.27% to 20.27%, respectively). There was about a 10% increase (from 38.03% to 48.65%) in the number of items involving the use of representations in post-lesson plans, and more questions requiring output-level thinking (from 22.54% to 33.78%) than input-level thinking (from 38.03% to 31.08%) were featured in post-lesson plans, which was the opposite in pre-lesson plans.

The results suggest that explicit instruction in spatial thinking enhanced participants' overall ability to incorporate spatial thinking into teaching. It is demonstrated particularly well by the increased number of complex-spatial concepts featured in the post-lesson plans. Enhanced understanding about spatial concepts as a result of learning in the workshop promoted the participants' confidence about teaching these concepts and therefore led to more incorporation of them into their lesson plans. The percent decreases for spatial primitives and simple-spatial concepts should be interpreted as a result of a shifting of priority between the concept categories (i.e., from spatial primitives to complex-spatial, from simple-spatial to complex-spatial) rather than decreases in the assessed value of spatial primitives or simple-spatial concepts. This is because the study

participants were asked to create only three lesson objectives and assessment items per lesson. If there were no limitations on number of objectives and assessment items that they could list, there might also be an increase in the number of spatial primitives and simple-spatial concepts. No evidence to support or dismiss this possibility is available, however.

As for the use of spatial representations as a teaching and learning tool in geography, there still seems to be much room for improvement. The percentage of objectives and assessment items associated with using and creating tools of representation increased on the post-lesson plans, but about 70 of the lesson objectives and over half the assessment items were still in the non-use category. Pre-service teachers seemed to find it challenging to create a lesson objective and assessment item that involves spatial representations, such as maps, graphs, and diagrams. That is because it requires comprehensive and integrated knowledge about the content and the ability to select and use spatial representations in an effective way for teaching. It also requires more time, effort, and skill to put things together. As some participants pointed out in the interview, they would need more time and practice to become capable of incorporating aspects of spatial thinking into their teaching practices. This is not surprising as it is consistent with findings from the literature that developing expertise in teaching spatial thinking needs extensive experience.

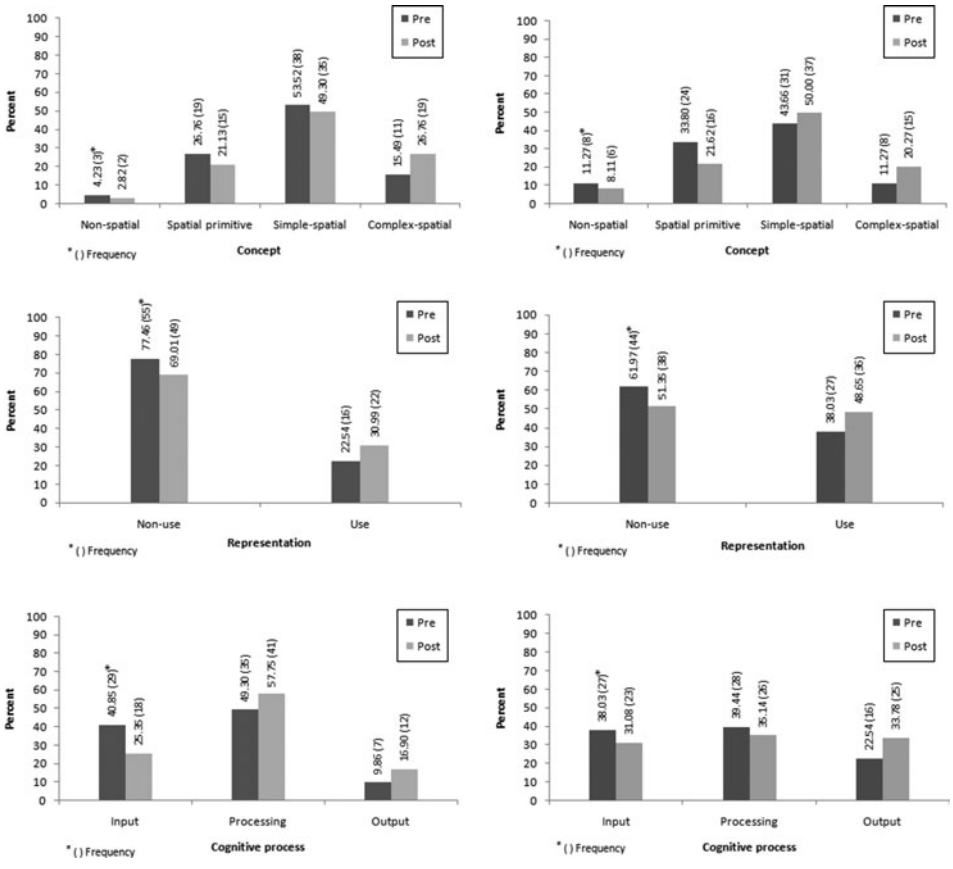


Figure 2. Spatiality of lesson objectives (left) and assessment items (right) in pre- and post-lesson plans.

The workshop was very successful in equipping participants with the ability to address higher level thinking. Percentages for output-level cognitive processes increased in both post-lesson objectives and assessment items. It is noteworthy, however, that participants made more effort to balance between low- and higher level thinking in designing assessments than in the lesson objectives. More specifically, the percentages for the three categories of cognitive processes were 31.08% for the input-level, 35.14% for the processing-level, and 33.78% for the output-level in the post-assessment items, whereas the corresponding percentages in the post-lesson objectives were 25.35%, 57.75%, and 16.90%, respectively. This might be a result of their explicit learning experience with assessment questions, analyzing and evaluating geography test questions from a spatial perspective, in the workshop where the importance of balance among different levels of cognitive processes to support student learning was explicitly discussed. If this is the case, a legitimate argument would be that pre-service teachers should be given such learning opportunities to ensure such balance when designing lessons and assessments.

Findings from a qualitative analysis: participant narratives

An analysis of the step-by-step instructional procedures component of the lesson plans allowed detection of four implementation strategies participants used to enhance their spatiality. First, participants allocated a block of time for teaching spatial concepts explicitly. They said (indicators of explicit teaching italicized):

> As a class, I will lead a discussion and *explicitly teach about what a region is.*
>
> [I will] present students with some background information on Canada's history and *define key concepts: region, density, etc.*

Second, participants began to use spatial concepts much more frequently, and the concepts of overlay, pattern, and distribution appeared particularly more in the post-lesson plans. An example is (concepts appear italicized):

> The students should then use the *overlay* technique to compare maps of the world's population *density* to maps of the *terrain* (including *profiles*), records of weather *patterns*, and maps which show various resources.

Third, spatial representations were utilized more often as a tool for teaching and learning. Not only did the participants use a wider variety of representations for their lecture purposes, but they also had the students use and create representations. The following quote illustrates such a case (student activities related to using or creating spatial representations italicized):

> The students also need to *create their own charts, graphs, diagrams* to portray information. Complete an example as a class in *making a chart or graph.*

Lastly, higher level cognitive processes were addressed more in the post-teaching and learning procedures as shown in the following (higher order thinking processes italicized):

> The students will write in their reflective journals their *speculations about the connections* between landscape, natural resources, and climate and human settlement patterns. The students may *hypothesize* that less people live in colder areas. The students then need to *explain why* they made their conclusions and how that influences today.

Participant narratives during the interviews verified that enhanced spatiality of the lesson plans and participants' conscious effort to incorporate spatial thinking into the lesson plans were a result of learning in the workshop. As for the aspect of spatial concepts, one participant said:

> I focused on the concepts because after doing the workshop, I found out that *my ideas of some concepts were different from the geography perspective of the concepts.* So, I tried to change as many as I could to fit that.

She realized that some of the spatial concepts have domain-specific meanings and usages that are somewhat different from those in ordinary vocabularies or in other domains. She tried to address this by explicitly teaching such concepts. Another participant said:

> [T]he main other difference [from pre- to post-lesson plans] was just *explicitly teaching what a region is* and then I went on from there. What I really got from the workshop was *not just assuming that my students know what these things are but explicitly describing them.*

What she learned in the workshop was that students are not likely to have sufficient knowledge about spatial concepts as many teachers might assume. Therefore, she would explicitly explain what a region is to ensure that her students knew the concept before learning about a world region.

Almost all participants stressed that they tried to increase the use of spatial representations as a teaching and learning tool. It was also found that incorporating more representations was often accompanied by higher order cognitive processes. For example, the following two quotes represent participants' effort to use maps as a means to help students be able to make comparisons and connections among the content.

> [W]hen [the teacher is] *making the comparison*, instead of just saying it, she can actually show them *a diagram*, which would be another visual to help the students.

> [B]ecause I really loved the idea of *combining maps together (overlay) to make students make connections.* I think that would help students make connections of why it's warmer in the Southern parts and why they would have those types of resources and industry there. So, that's why I was really focused on adding that.

Several participants used spatial representations to facilitate students' interdisciplinary thinking and critical thinking, as exemplified in the following:

> [T]hey are *making their own and using it [a graph]* . . . because it gives them more practice. It is related to math as well and spatial thinking and it is used in a social studies context so it is kind of *interdisciplinary*.

Participants also made explicit effort to have their students go through higher level cognitive processes during the lesson. For example, they changed input-level thinking in their pre-lesson plans to processing-level in their post-lesson plans:

> I used *compare and contrast* because I learned the terms. I learned the different taxonomy, and I wanted to use that. I felt the students would get more out of it than just if I asked them to *name something*.

Participants' effort to address output-level thinking in their post-lesson plans, such as asking students to justify their decisions and to create a representation, was also observed as in the following example:

> [In the pre-lesson plan] I basically said that they *were listening to and creating a booklet and showing it* and that was it. In the second one [post-lesson plan], that part of the assessment was to where they *utilized maps, graphs, and charts in their booklets and while they presented it, they explained their reasoning for choosing* because I gave them the option of choosing which visual.

Conclusions

With the view of a teacher as a curricular-instructional gatekeeper (Thornton, 1989), the authors believe that well-prepared teachers are key to the successful implementation of spatial thinking into classrooms. This study examined whether explicit instruction in

spatial thinking enhances pre-service teachers' PCK for teaching it. The results of quantitative analysis of the lesson plans indicate that the workshop helped pre-service teachers develop their PCK for teaching spatial thinking as evidenced by the increased frequencies of the three components of spatial thinking featured in the post-lesson plans. Findings from the qualitative analysis suggest that the learning experiences and activities in the workshop provided them with opportunities to actually practice how to incorporate spatial thinking into a variety of teaching strategies.

Implications of this study for the focus, methods, and approaches to geography teacher preparation include first, explicit learning about spatial thinking is essential when developing pre-service teachers' PCK to teach spatial thinking through geography. Most of the participants had taken one or two geography courses and several more education courses by the time of the study. However, they were neither able to grasp the spatial perspectives of geography and the role of representations in geography learning nor capable of making connections between the content knowledge learned in geography courses and pedagogical knowledge learned in education courses. Simply speaking, they lacked PCK to teach spatial thinking. The present study provides empirical evidence that pre-service teachers' knowledge acquired from geography courses and educational courses is not readily translated into their PCK to teach spatial thinking. Despite the short duration of the workshop, explicit learning about spatial thinking and practice incorporating it into teaching seems to be more effective. Whether this will be true in other educational contexts remains untested, though.

Second, this study indicates that it is critical for pre-service teachers to have opportunities to see an exemplary classroom lesson in which the three aspects of spatial thinking are well infused. Many of the participants said that watching the video of an expert geography teacher's lesson and analyzing it from a spatial perspective helped them understand what it means to teach spatial thinking through geography. Most participants said that they had not had a single experience evaluating classroom teaching. Even for those who had prior experiences of classroom observation and evaluation of teaching practices, the evaluation criteria focused largely on the teacher's classroom management skills. None of the participants said that they had evaluated someone else's teaching from a content perspective, let alone from a spatial perspective. The implication is clear: pre-service teachers need opportunities to observe expert teachers' practices, to analyze it from a spatial perspective, and to reflect on it to inform their future practices.

Third, pre-service teachers should practice the skills to design questions and assessment items that can facilitate students' practice of spatial thinking. It is well understood that questions are significant educational tools that can stimulate students' thinking (Pizzini, Shepardson, & Abell, 1992; Vogler, 2005; Wilen, 2001). Research suggests, however, that not all questions are equally effective in leading students to think (Costa, 2001; Hamaker, 1986; Mills, Rice, Berliner, & Rosseau, 1980; Nosich, 2005). Research found that the cognitive levels required to answer questions in geography textbooks were quite low as was their degree of spatiality (Jo & Bednarz, 2009). Considering the importance of questions and assessments in education and the low spatiality of the questions in typical curricula materials, it is important that teachers possess critical eyes to select, design, and use effective questions to facilitate students' spatial thinking. Teachers' assessment skills do not automatically develop with mere repetition of teaching routines but rather develop with deliberate and purposeful practice. Therefore, geography teacher preparation programs should offer learning opportunities for deliberate practice in developing questions and assessments that stimulate students' spatial thinking.

Another implication involves the importance of providing tangible tools, such as a taxonomy of spatial thinking (Jo & Bednarz, 2009), which they can keep utilizing and referring to as a resource. The usefulness of educational taxonomies for teaching and assessing student learning has long been recognized, particularly since the release of the iconic tool developed by Bloom, Engelhart, Furst, Hill, and Krathwohl (1956). Most of the study participants were aware of Bloom's Taxonomy, and some had experiences creating higher order thinking questions using it. However, as pointed out by Jo, Bednarz, and Metoyer (2010):

> Bloom's Taxonomy does not address the two major components of spatial thinking – knowledge about spatial concepts and ability to use tools of representation, limiting its usefulness as a framework to select and design questions to support spatial thinking. (p. 51)

The taxonomy of spatial thinking used in this study, on the other hand, addresses the three key components of spatial thinking explicitly. The taxonomy helped participants learn a practical method to integrate the three components into teaching practice, analyze and improve their questions, and ensure the balance between lower level and higher level thinking in their questions.

Further research is definitely needed. One reasonable step would be to examine in-service practices of the study participants to see how their enhanced awareness of spatial thinking and knowledge about geospatial concepts are reflected in their teaching practices. Such a longitudinal study would help reevaluate the effectiveness of the workshop in a real-world context.

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