Computers & Education 76 (2014) 225–236

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

The effects of geography lessons with geospatial technologies on the development of high school students' relational thinking

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
28 February 2014
Accepted 1 April 2014
Available online 16 April 2014

Keywords:
ICT
Secondary geography education
Relational thinking
Systems thinking
Spatial thinking

Keywords from the list:
Applications in subject areas
Improving classroom teaching
Interactive learning environments
Secondary education
Teaching/learning strategies

ABSTRACT

Geospatial technologies offer access to geospatial information via digital representations, such as digital maps, and tools for interaction with those representations. The question is whether geography lessons with geospatial technologies really contribute to the development of students' geospatial thinking, in particular geospatial relational thinking, as is suggested in the literature about geospatial technologies in secondary education. This paper reports about the outcomes of a quasi-experimental research project, in which a geography lesson series with geospatial technologies was compared with a conventional geography lesson series that had the same content. Although the lesson series covered only three lessons, the data showed that the lesson series with geospatial technologies contributed significantly more to the development of students' geospatial relational thinking than the conventional lesson series. The effect size was 'medium large'.

1. Introduction

Challenges in the world around us, such as climate change challenges, food challenges, poverty challenges, energy challenges, migration challenges, city planning challenges, and natural hazard challenges, are growing in complexity. They exist at scales ranging from local to global, cut across human and natural systems, involve many interdependent variables that are changing over time, and have a strong spatial component. These challenges are important for our future, but are difficult to understand, predict, and solve. One of the main goals of secondary geography education is to provide students with the ability to translate the challenges that they observe or read about, into a more coherent understanding. Also, they should learn to reason about solutions for these challenges, and to formulate judgements about these solutions, so that they can make informed decisions in their future everyday and professional lives. A growing number of educators worldwide have become convinced that the ability to think spatially is key to the development of these competences, and that education with geospatial technologies may contribute to the development of spatial thinking (e.g. Kerski, 2008; Lee & Bednarz, 2009; National Research Council, 2006). However, little is known about the effectiveness of instruction with geospatial technologies. This paper investigates the learning outcomes of a lesson series with geospatial technologies on one of the components of spatial thinking: spatial relational thinking.

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http://dx.doi.org/10.1016/j.compedu.2014.04.004
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2. Spatial thinking and relational thinking

Spatial thinking is a kind of thinking that has been receiving more and more attention from educators in the past ten years. It refers to the knowledge, skills, and habits of mind related to the use of: concepts of space; tools of spatial representation; and processes of spatial reasoning (National Research Council, 2006). According to the authors of the influential book “Learning to think spatially”, spatial thinking is universal kind of thinking that is useful in a wide variety of academic disciplines and everyday problem-solving situations (National Research Council, 2006). Huynh and Sharpe (2013, p. 3) argue that spatial thinking is “core to the theoretical and practical underpinnings of geography”. Spatial thinking within the geography domain is somewhat different from spatial thinking in other domains. Geographers typically use a *geo*spatial reference frame. They study problems that are connected to locations on Earth, rather than problems in abstract thinking spaces. In other words: for geographers, the place on Earth matters.

Spatial thinking consists of several distinct but interrelated abilities. It is somewhat broader than *spatial ability*, although the two are related to each other (Lee & Bednarz, 2009). Cognitive psychologists (e.g. McGee, 1979) and geographers (e.g. Huynh & Sharpe, 2013; Lee & Bednarz, 2009) generally agree that two key components are ‘spatial visualization’ and ‘spatial orientation’. *Spatial visualization* is the ability to mentally manipulate, rotate, twist, or invert individual objects (McGee, 1979), while *spatial orientation* is the ability to determine the relative position of objects, to change the point of view, and to maintain a sense of direction when moving through an environment. However, there is some disagreement about whether a third component, ‘spatial relations’, is also part of spatial ability (Gilmartin & Patton, 1984; Golledge & Stimson, 1997; Lohman, 1979; Montello, Lovelace, Golledge, & Self, 1999). Many geographers argue that the ability to reason about spatial distributions and patterns, spatial interactions, and spatial relations is an important part of spatial thinking (Albert & Golledge, 1999; Bednarz, 2004; Gilmartin & Patton, 1984; Golledge & Stimson, 1997; Huynh & Sharpe, 2013; Lee & Bednarz, 2009; Self & Golledge, 1994). The spatial relations component is the most often addressed component in geography courses (Bednarz, 2004), and Huynh and Sharpe (2013) argue that it’s the geospatial reference frame and the focus on spatial relations what make geospatial thinking different from the general kind of spatial thinking.

Although many geographers argue that the spatial relations component is the most important component of geospatial thinking, it is also the least clearly defined component (Lee & Bednarz, 2009). According to Golledge and Stimson (1997, p. 158), the spatial relations component includes the ability “to recognize spatial distributions and spatial patterns, to connect locations, to associate and correlate spatially distributed phenomena, to comprehend and use spatial hierarchies, to regionalize, to orientate to real-world frames of reference, to imagine maps from verbal descriptions, to sketch maps, to compare maps, and to overlay and dissolve maps”. Although this description of the spatial relations component has formed the basis for several geospatial thinking tests (among others: Huynh & Sharpe, 2013; Lee & Bednarz, 2009), it has some shortcomings.

First, many of the subcomponents in Golledge and Stimson’s definition of the spatial relations component are not directly linked with spatial relations. For example, recognizing spatial patterns can be a prerequisite for recognizing spatial associations, as it requires one to compare two spatial patterns to see if there is any match. However, recognizing spatial patterns can also be a goal *in itself*.

Second, the terms contain different verbs, such as: ‘recognizing’, ‘connecting’, ‘comprehending’. Most refer to the construction of new knowledge. This is a somewhat limited view on spatial thinking, as it hardly addresses spatial reasoning skills. For example, students should not only be able to recognize spatial distributions and spatial patterns, but should also be able to explain them, and to reason how they might change in the future due to autonomous processes or as a result of human interventions in the system. This kind of reasoning requires them to structure and apply their knowledge about spatial associations or causal relations. These spatial reasoning processes are an important part of spatial thinking, as they are needed to understand, for example: how the Arab Spring is related to the heat wave in Russia in 2010; why some glaciers in South Norway are advancing, while they are retreating in the rest of the world; and why the construction of the Erie Canal resulted in an economic boom in New York, while the construction of the Beaver Canal failed to do the same for Philadelphia.

For the reasons outlined above, it might be better to change the name of the component from ‘spatial relations’ to ‘spatial analysis and spatial reasoning’, and to distinguish a subcomponent called ‘geospatial relational thinking’. It is clear now that this subcomponent goes much further than recognizing spatial associations alone, as it also includes geospatial relational reasoning processes. The subcomponent connects to *systems thinking*, which is a holistic approach that focuses on how the constituent parts of a system are related to each other, how such systems respond to changes, and how systems work within the context of larger systems. It aims to provide insight into how things influence one another within a whole system over time, based on the belief that the components of a system can best be understood in the context of relations with each other and with other systems, rather than in isolation. Systems thinking often focuses on cyclical cause and effect. Attention to feedback mechanisms, with their reinforcing effects (positive feedbacks loops) or balancing effects (negative feedback loops), is an essential component of systems thinking.

Systems thinking is well anchored in the earth sciences tradition, which is one of the four traditions in geography distinguished by Pattison (1964). An *earth systems thinking* approach views the world as a system that consists of four central subsystems (Mayer, 1995): the geosphere, the hydrosphere, the atmosphere, and the biosphere (including humans). Orion’s (2002) didactic model for science education based on the earth systems approach emphasizes the study of geochemical and biogeochemical cycles in the different subsystems (e.g. the rock cycle, the water cycle, the food chain, the carbon cycle, and the energy cycles), and the interrelations between those subsystems through the transfer of matter and energy from one subsystem to another. In order to be able to reason about relations in such systems, students should develop a dynamic, cyclic, and systematic representation of these systems, thereby taking feedback mechanisms, stocks, and time lags into account (Kali, Orion, & Elon, 2003).

Although earth systems thinking and geospatial relational thinking both aim to structure the complexity of systems, there are also several differences. The first difference is that earth systems thinking solely focuses on physical and chemical processes, while geospatial relational thinking focuses on the natural system, the human system, and the relations between these two systems. Van der Schee (2000) distinguishes two types of relations: vertical relations; and horizontal relations. *Vertical relations* are relations *within* regions, such as the relations between different physical geographic properties in a region (e.g. soil, climate, hydrology, ecology) and relations between different human geographic properties (e.g. demography, sociology, economies, politics) in a region, and human–nature relations. As regions are situated in networks, and as flows may occur between regions, a change in a property of one region may result in a change in a property of another region. This is called a *horizontal relation*. Because of these horizontal relations, the interlinked natural system and human system can be seen as a *spatial system*. This system provides opportunities and challenges for different land-use functions (e.g. residential, transport, agriculture, recreation, nature). In turn, land-use functions can affect the system via environmental pollution, groundwater extraction, fertilizing, etc. People can apply planning measures to change the system, and in such a way optimize the opportunities and decrease the challenges.

The second difference lies in the analysis level. In geospatial relational thinking, the analysis units are concrete regions (e.g. 'the Dutch Delta Region'), while in earth systems thinking, the analysis units are usually more abstract system components (e.g. 'the atmosphere'). For example, geographers can reason about the effects of sea level rise on salinisation in the polders of the Dutch Delta Region, thereby taking the flow of salt groundwater from the estuaries to the polders into account. In contrast, earth scientists can reason about the effects of CO_2 emissions on climate, thereby taking flows of carbon between the atmosphere, hydrosphere, biosphere, and geosphere into account. So, in contrast to earth systems thinking, the relations in geospatial relational thinking are connected to concrete geospatial units: regions, places, etc.

The third difference lies in the kind of representations that are used to study relations. Kim (1990) argues that systems thinkers can use at least ten different kinds of tools. Maps are not included in Kim's list, while they are one of the most important sources of information about geospatial relations, as they can show the match between two spatial distributions or spatial patterns or show the flow of people, products, money, etc. between regions. Besides maps, geographers also often use time charts, scatterplots and conceptual frameworks of causal relations, just as earth system thinkers.

Conclusively, we can say that geospatial relational thinking is a deep kind of thinking which has some links with systems thinking. Geospatial relational thinking is an important part of geospatial thinking, which is a valuable way of thinking to analyse and reason about the big challenges in the world around us.

Geospatial technologies seem to hold promising opportunities for stimulating students' geospatial relational thinking and other aspects of geospatial thinking. The next section discusses how geospatial technologies can be used to stimulate the development of geospatial (relational) thinking, and what is known about the learning effects of lessons series with geospatial technologies on students' geospatial (relational) thinking.

3. Geospatial technologies

One of the main innovations in geography teaching in the past few decades has been the introduction and diffusion of *geospatial technologies*, which are technologies that offer access to geospatial information via digital representations (such as digital maps), and tools for interaction with those representations. Geospatial technologies allow us to work with large quantities of detailed, authentic and up-to-date geospatial information in a fast, flexible, and user-friendly way. Well-known types of geospatial technologies are *global positioning systems* (GPS) and *virtual globes* such as Google Earth. Another type of Geospatial technologies is *desktop GIS (Geographic Information Systems)*, which is professional software for visualising, creating, manipulating, querying, analysing and presenting digital maps. Desktop GIS is widely used in business, government and science for studying spatial problems and exploring solutions for these problems. Recently, a large range of *WebGIS* applications have become available: websites that contain a interactive windows for viewing maps and other kinds of geospatial information. They generally offer far less tools and an easier interface than desktop GIS (Kim, Kim, & Lee, 2013; Milson & Earle, 2007). Some WebGIS applications are specifically developed for use in secondary education, and can be seen as a sort of 'web-based atlas'. A special category of geospatial technologies are *serious geogames*, which are games based on a schematic map and a computer model. They are not only entertaining, but also aim to educate students about specific geographic problems.

Geospatial technologies offer many opportunities for designing interesting and challenging geography lessons. Bednarz and Van der Schee (2006) argue that they can be used to raise students' understanding of local to global issues. They can also be used to train important skills, such as: analytical skills; critical thinking skills; communication skills; and inquiry skills (e.g. Audet & Ludwig, 2000; Demirci, Karaburun, & Unlu, 2013; Favier & Van der Schee, 2012; Kerski, 2003; Milson, Demirci, & Kerski, 2012). Besides this, many authors argue that geospatial technologies offer many opportunities for stimulating geographic thinking skills, in particular: geospatial thinking skills (Bednarz, 2004; Huynh & Sharpe, 2013; Lee & Bednarz, 2009; National Research Council, 2006; Nielsen, Oberle, & Sugumaran, 2011). Regarding the development of students' geospatial relational thinking, we can identify seven major advantages of geospatial technologies over traditional means (e.g. paper maps):

1) Many geospatial technologies offer enormous amounts of map layers about interrelated phenomena. As the map layers cover the same regions and have the same aggregation levels, students can easily explore them to see if there are any associations (Bednarz & Van der Schee, 2006).
2) Most geospatial technologies allow students to stack map layers on top of each other, to switch them on and off, and to make them transparent. Some applications also offer the possibility to put map layers next to each other. These functionalities make it easier for students to identify spatial associations (Bednarz & Van der Schee, 2006).
3) Some applications offer additional textual, audio, or video information about regions and phenomena. See, for example, the Wikipedia and YouTube layer in Google Earth. This can provide additional information about the geographic system, which can help students construct knowledge about cause-and-effect.
4) Some geospatial technologies allow students to investigate geodata in coupled representations: maps; tables; and scatterplots. When students select a region on the map, the region also blinks in the table, and in the scatterplot. This also makes it easier for them to identify spatial associations. Furthermore, working with such coupled representations often generate questions about why a region has specific property values, why the property value is an exception to the rule, etc. In other words, it stimulates them to think about the relations that underlie the geodata.
5) Some geospatial technologies allow students to calculate the strength of associations (correlation coefficients). This makes it possible to follow a more quantitative approach to studying relations (Yano, 2000).
6) Many geospatial technologies offer the possibility to display temporal geodata in animated maps, histograms, temporal charts, and scatterplots (Rosling, 2007). Students can explore these animations, in order to identify associations in the geodata.

7) Geospatial technologies such as serious geogames allow students to evaluate the effects of planning measures on the geographic system, and therefore provide insight into the different relations in the system. Research has shown that well-designed educational games embedded in proper instruction can be motivational for students and can aid to the development of higher order thinking skills (Hainey, Connolly, Stansfield, & Boyle, 2011).

The characteristics of geospatial technologies outlined above enable teachers to develop instruction methods that aim to stimulate geospatial relational thinking skills that are often difficult to address. This connects to Palladino and Goodchild's (1993) argument that geospatial technologies make it easier to engage students in 'higher order thinking activities that are often so hard to come up with.' The design of geography lessons with geospatial technologies is also often very different from the design of traditional geography lessons. Lessons with geospatial technologies are often learner-centred, and their designs connect to (socio)constructivistic learning theories. In such a way, geospatial technologies have the potential to fundamentally alter the manner of teaching and learning in the classroom (Baker & White, 2003; Kerski, 2003; Sinton & Lund, 2007).

Until the beginning of the 21st century, the adoption of geospatial technologies in schools proceeded slowly (Aladag, 2009; Cremer, Richter, & Schäfer, 2004; Doering & Veletsianos, 2007; Kerski, 2003; Lam, Lai, & Wong, 2009; Shin, 2006; Zink & Scheffer, 2009). Often-cited barriers include (Milson & Kerski, 2012): the lack of hardware, software, and instruction materials; teachers' limited competencies in teaching with geospatial technologies; and the absence of clear educational standards for geospatial technologies. However, in the past five years or so, not only have computer facilities at schools improved, but also a wide range of free and user-friendly web-based applications and instruction materials have become available (Kim et al., 2013). Furthermore, geospatial technologies have now been included in the curricula of more countries. Hence, many teachers have started making a first step (Milson et al., 2012). Still, there are some important challenges to the further diffusion of geospatial technologies in schools. One of the frequently cited challenges is that little is known about the effectiveness of lessons with geospatial technologies compared with lessons using analogue materials (i.e. paper maps). Some teachers argue that integrating geospatial technologies might not be worth the extra effort. In a survey on the implementation of geospatial technologies in secondary education, one teacher expressed concerns about the effects of geospatial technologies on learning (Kerski, 2003: p. 133):

> *'I personally have been troubled with the question of whether students are learning geographic inquiry strategies or merely learning to use a very powerful tool without much thinking about the underlying questions under consideration.'*

The lack of experimental research in the field of geography education and geospatial technologies was first noticed by Baker and Bednarz in 2003, and has been underlined by other authors since (Kerski, 2008). Even today, scientific papers that report about the outcomes of experimental research on the effectiveness of teaching with geospatial technologies are scarce (Demirci et al., 2013; Kim et al., 2013), especially when it concerns the effects on specific thinking skills. There are some studies that showed significant higher achievement for lessons with GIS (e.g. Baker & White, 2003; Goldstein & Alibrandi, 2013; Lee & Bednarz, 2009). However, geospatial relational reasoning is not addressed in any of these studies. Existing standardized tests, spatial thinking tests, and spatial analysis tests do not fully test the skills that students need to reason about the big challenges in the world around us, nor do they test the full width of geospatial relational thinking skills that can be addressed in instruction methods with geospatial technologies. The problem is that in the spatial thinking literature, the focus is often on learning to use (complex) geospatial technologies and its geospatial analysis methods, while the focus should be more on learning to analyse and reason about the challenges in the world around us. Each of these studies made use of desktop GIS applications, a kind of geospatial technology that has been known for its complexity (Kim et al., 2013). Therefore, a large number of lessons were spent on 'learning how to handle the technology' rather than 'learning how to analyse and reason about the challenges in the world around us'. The complexity of desktop GIS software and the time needed to master the software are barriers for incorporating GIS into the classroom (Bodzin & Anastasio, 2006; Kim et al., 2013; Milson & Earle, 2007). Today, young people are familiar with technology, but they are also easily frustrated when technology is not intuitive (Nielsen et al., 2011). Therefore, several authors (e.g. Golledge, Marsh, & Battersby, 2007; Kim et al., 2013) have argued that educators should use simple geospatial technologies, so called 'minimal GIS'. Such geospatial technologies can play a critical role in realizing the pedagogical potential of geospatial technologies.

So, in summary, it is evident that although many educators have the feeling that teaching and learning with geospatial technologies can contribute to higher achievement in geospatial thinking, there is still little concrete evidence for this assumption, especially as it concerns geospatial relational thinking.

4. Research questions

This paper attempts to contribute to knowledge development in the field of geography education with geospatial technologies, by investigating the effects of a geography lesson series with geospatial technologies. The main questions of the research are: (1) 'What are the effects of a lesson series with geospatial technologies on high school students' achievement in geospatial relational thinking, compared with a conventional lesson series which focuses on the same content?'; and (2) 'What are students' perceptions about the learning effects of a lesson series with geospatial technologies, compared with a conventional lesson series?'.

5. Methods

5.1. Research design

A quasi-experimental approach was followed to get more insight into the relation between the type of instruction (independent variable), the scores on a geospatial relational thinking test (dependent variable 1), and students' perception of the learning effects (dependent variable 2). The research consisted of an experimental group who followed a lesson series with geospatial technologies, and a control group who followed a conventional lesson series. Students in both test groups did a pre-test (30 min); then followed a series of three lessons

(3 × 45 min); and, finally, did a post-test (30 min). In order to investigate the differences in students' perceptions about the learning effects of the lesson series, a survey was included at the end of the pre-test and post-test.

5.2. *Test groups*

Tests were conducted at five different schools in the Netherlands, in 3rd grade HAVO (General Secondary Education) and 3rd grade VWO (Pre-university Secondary Education). This is comparable to 9th grade high school classes in the USA. The students were 14–15 years old. Table 1 presents the characteristics of the test groups.

Classes were assigned to the two conditions. Each teacher had two classes: one that followed a lesson series with geospatial technologies (the experimental class); and one that followed the conventional lesson series. Over 300 students participated in the research, but only those students who completed the entire lesson series and both tests were included in the data analysis: 139 students in the experimental condition, and 148 students in the control condition.

In many respects, the five schools were quite similar. They were all located in small to mid-sized towns of 30,000–300,000 inhabitants in the Western part of the Netherlands. They had 800 to 1400 students, with a low (<5%) population of students with a non-European background. All five schools scored 0.1 to 0.2 point higher than the national average on national exams (SchoolVO, 2013).

5.3. *Design of the lesson series*

The lesson series focused on water-related spatial planning issues in two regions in the Netherlands: the Delta Region; and the River Region. In this research, the main requirement of the lesson series was that the lesson series of both the control group and the experimental group should be realistic for the present educational context. The lesson series should fit with the geography curriculum, and should fit with the skills of the average teacher (no special training should be needed, and teachers should be able to conduct the lesson series without assistance).

The *control group* followed a conventional lesson series that was based on the schoolbook '*Buitenland*'. Most lessons started with a discussion of the texts, pictures and maps in the textbook. Some teachers used additional sources of information about water-related planning issues, such as YouTube videos and newspaper articles. After this introduction, students subsequently worked on assignments in the workbook. These assignments mainly focused on the properties and structures of the water system in the Delta Region and River Region in the Netherlands, and, to a lesser extent, on the functioning of the system. Spatial planning measures were explicitly listed in the textbook. Most teachers organized a classroom discussion at the end of each lesson, in which they discussed part of the assignments.

Students in the *experimental group* followed a lesson series with geospatial technologies. In the first two lessons, students followed a module of *The Water Manager*, a serious geogame for secondary education. The game consists of two modules: one about the Delta Region, and one about the River Region. The game uses schematic maps of the two regions (Fig. 1). In the game, students take the role of water manager. They have to find an optimal solution for water-related challenges (increased flood risk) in schematic maps of the Delta Region and River Region. They can select different kinds of measures, and drag these measures to different places in the schematic map (Fig. 1). A simulation subsequently shows the effects on the system, and on the different land-use functions. Students can see that the effects of measures depend on the local circumstances, and that measures also often have effects in other regions (i.e. upstream or downstream). In order to obtain a maximum number of points, students have to carefully weigh the effects on the different planning measures. After gaming, students work on assignments in which they have to summarise the system rules: they have to draw arrows in a conceptual framework that represent the relations between measures and land-use functions (Fig. 2). Research by Hwang, Yang, and Wang (2013) showed that integrating concept mapping in game-based instruction can significantly improve the learning outcomes, as it helps them organize what they have learning during the game-based learning process.

After the lesson with the game, students then switch to another application: *EduGIS*, a webatlas for secondary education in the Netherlands. Students have to investigate which measures were taken in the Delta Region and River Region in the context of the 'Delta Works programme' and 'Room for the Rivers programme', and why these measures were taken at these locations. They have to study digital maps, like a land-use map, a map of the population density and a water system map, in order to answer these questions. In addition, they have to apply the system knowledge they have developed when playing the game.

In the final lesson, students also investigated the safety norms of different polders in the Netherlands with the help of EduGIS maps. Safety norms are set by the Dutch government, and the height of dykes around polders is based on the safety norm of those polders. The safety norm depends on the number of inhabitants and economic value of the polder, the type of water threat (sea, river or lake), and the water depth in case of a dyke breach, In the EduGIS assignment, the students had to investigate these relations by studying map layers of these properties of polders (Fig. 3). They are thereby stimulated to vary one variable while keeping the others constant. So the assignment

Table 1
Characteristics of the test groups.

School	Teacher	Condition					
		Experimental group	*N* (male)	*N* (female)	Control group	*N* (male)	*N* (female)
A	A1	3rd grade VWO	12	8	3rd grade VWO	10	15
B	B1	3rd grade VWO	16	10	3rd grade VWO	11	10
C	C1	3rd grade HAVO	14	12	3rd grade HAVO	12	16
	C2	3rd grade HAVO	12	18	3rd grade VWO	15	14
D	D1	3rd grade VWO	9	10	3rd grade HAVO	7	14
E	E1	3rd grade VWO	11	7	3rd grade VWO	12	12
		Total	74	65	*Total*	67	81
		Total	139		*Total*	148	

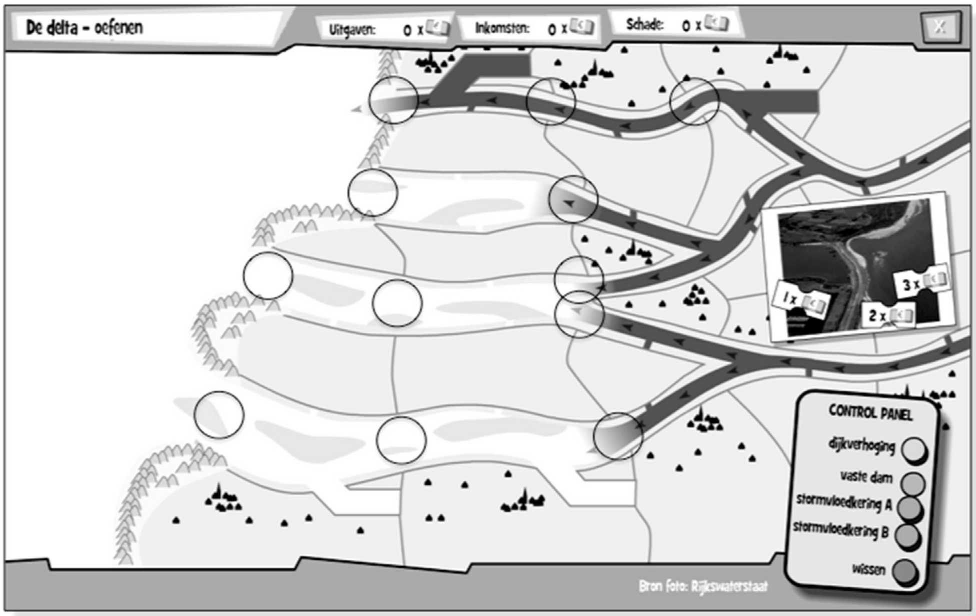

Fig. 1. A screenshot of *The Water Manager*. The figure shows the sites where students can build the measure: "dam".

can be seen as a 'control of variables strategy' task. They also had to make the causal relations explicit, and draw them in a partially completed conceptual framework.

In summary, the lesson series in the experiment group and control group covered exactly the same topics and issues. However, the lesson series with geospatial technologies placed more emphasis on *systematic* thinking about geospatial relations. As the lesson series with geospatial technologies was very short, only two applications could be used. It was, therefore, not possible to make use of all seven advantages of geospatial technologies for stimulating students' geospatial relational thinking (see Section 3). Only advantages 2 and 7 were implemented.

In this research, existing educational geospatial technologies were used, without making adaptations to the applications. EduGIS and the Watermanager are readily available for teachers via the Internet without costs (www.edugis.nl and www.watereducatie.nl). Both applications are very intuitive and user-friendly. They connect with the idea of 'minimal GIS' (Kim et al., 2013). EduGIS has been developed since 2005, by a consortium of, among others: VU University Amsterdam, Geodan (a geospatial technology and data consultancy), and Kadaster (the Dutch Ordnance Survey). The application is used by more than 50% of the teachers in The Netherlands. The Watermanager has been developed by the VU University, commissioned by the National Water Education Board. The number of teachers who use The Watermanager is probably less than 5%, as it is a relatively recent application.

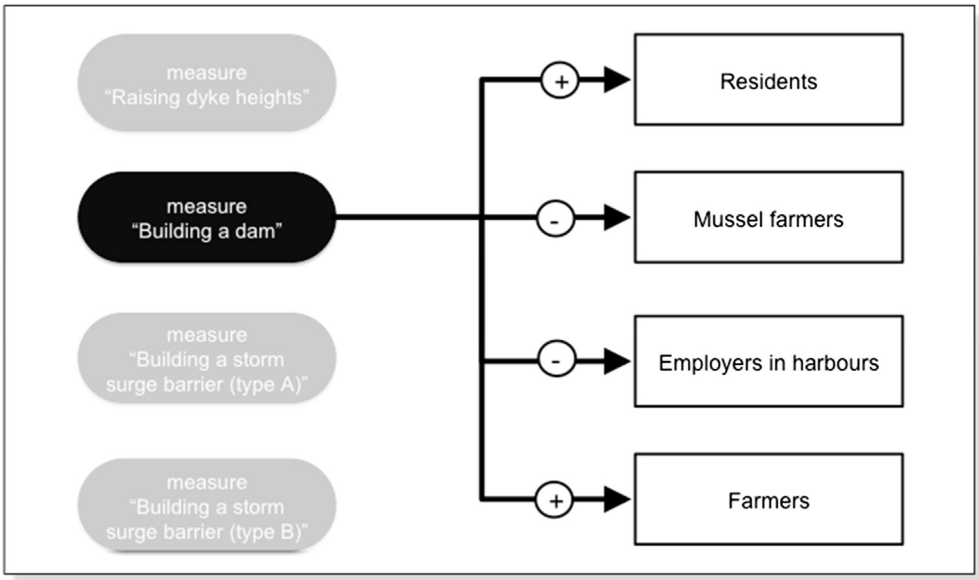

Fig. 2. Assignment in which students had to complete a framework of causal relationships. The figure shows the effects of the measure "dam".

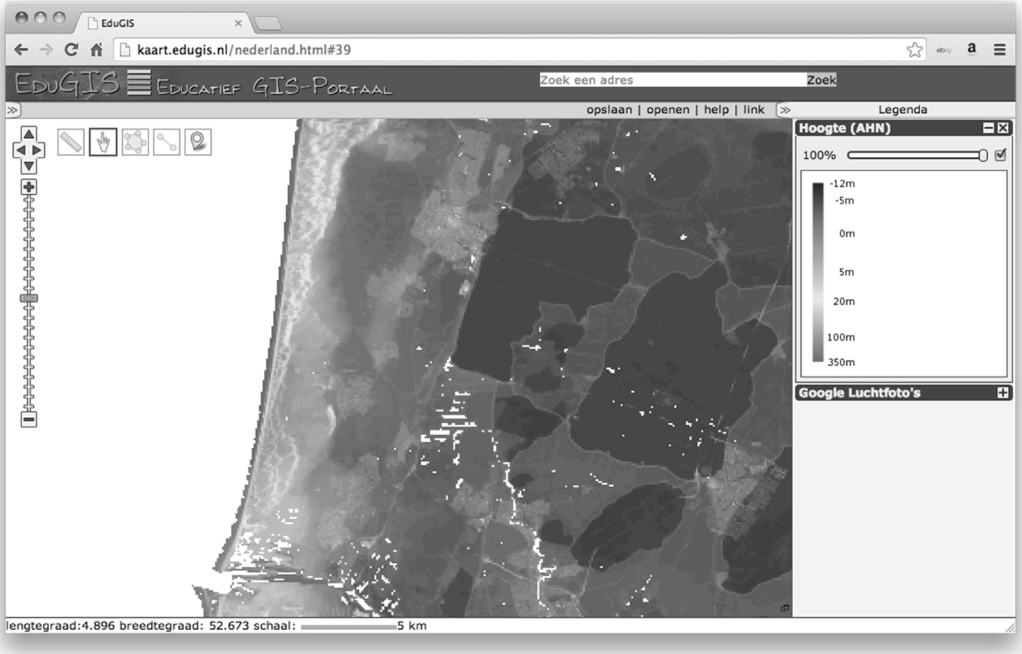

Fig. 3. Screenshots of *EduGIS*. The figure shows the elevation map.

5.4. Design of the test

As existing spatial thinking tests (e.g. Huynh & Sharpe, 2013; Lee & Bednarz, 2009) cover only a small part of geospatial relational thinking, a new test was developed by the authors of this paper, building on the revised Bloom Taxonomy (Anderson & Krathwohl, 2001), the literature about spatial thinking (see Section 2), earth systems thinking (see Section 2), map skills (e.g. Van der Schee, Van Dijk, & Van Westrhenen, 1992), and geographic thinking (e.g. KNAG, 2003). The test was discussed and validated with teachers. The test consisted of six test items (Table 2). The *first and second items* were 'control of variables strategy' (CVS) test items (Chen & Klahr, 1999), in which students had to identify relations in representations. The first dealt about a non-geographic topic. Students had to analyse a figure that contained eight different paper planes, and the test results for each plane (the distance covered). Students were asked which factors determine how far a plane can fly. In order to answer the question, students had to compare planes that are similar except for one property. In the second test item, students had to analyse a water-related problem that was not covered by the lesson series, either in the experimental or in the control group: the salinisation of the polders in the Western part of the Netherlands. Students were shown eight schematic maps and cross-sections from the sea to a polder, and were asked to identify the factors that determine the degree of salinisation in a polder. In order to answer the question, students had to compare cross-sections that are similar except for one property. Both test items aimed to provide insight into the degree to which students were able to identify relations in representations, but the representations in item 2 were more difficult to analyse than the representations in item 1.

The *third and fourth test items* were 'conceptual framework completion tasks', in which students had to fill out a partially completed conceptual framework of causal relations. In the third test item, they were asked to draw arrows between boxes with the causes and effects of the 1953 floods in the southwest of the Netherlands. The content was not very difficult, and students were expected to possess the required knowledge. In the fourth item, students had to fill out a partially completed conceptual framework about the factors that are related to the water level in a lake. Students were asked to draw arrows between different variables: water level; inflow; outflow; precipitation; evaporation; and temperature. The content of this test item is more difficult to structure than the content of the third test item, but again, students were expected to possess the required knowledge. The two test items aimed to provide insight into the degree to which students were able to organize their knowledge about relations in a conceptual framework. Test item 4 contained more relations than test item 3, and the relations were also more complex.

Table 2
Characteristics of the test items of the pre-test and post-test.

Nr	Content	Type	Tested processes
1	Aeroplanes	CVS task	Identifying non-spatial relationships in representations
2	Salinisation	CVS task	Identifying geospatial relationships in geospatial representations
3	Floods of 1953	Conceptual framework completion task	Organizing geospatial relationships
4	Water level in a lake	Conceptual framework completion task	Organizing geospatial relationships
5	Fictive delta	Design task	Evaluating measures and creating solutions
6	Real river	Design task	Evaluating measures and creating solutions

The *fifth and sixth test items* were semi-open design tasks. In the fifth test item, students had to plan measures in a schematic map of a fictive delta system in order to prevent the delta from flooding and to make sure that there is enough fresh water available for agriculture, while making sure that other land-use functions (mussel farming and freight shipping) can continue. This fictive delta system had different properties from the Delta Region in the Netherlands, while the measures that students could choose from were similar to the measures discussed in both the experimental and the conventional lesson series. The sixth test item focused on rivers. This item used a real topographic map instead of a schematic map, and required more complex geospatial relational thinking. Students had to plan measures in a Dutch river (that was not covered by either one of the lesson series) in order to decrease the flood chance. The two items provided insight into the degree to which students understood the functioning of the water system, and the degree to which they were able to evaluate the effects of measures, and create an optimal solution for the problems in the two regions.

5.5. Design of the survey

In order to investigate the differences in students' perceptions about the learning effects of the lesson series, a survey was conducted that contained three questions: 'How much knowledge do you have about the *characteristics* of the water system in the Delta Region and the River Region?'; 'How much knowledge do you have about the *functioning* of the water system in the Delta Region and the River Region'; and 'How much knowledge do you have about the *water-related problems* in the Delta Region and the River Region'. Students were asked to rate their knowledge on a 1-to-5 point Likert scale. The survey was included at the end of the pre-test and post-test, which enabled us to investigate in which degree students think their knowledge has increased.

5.6. Data analysis

The whole project (two times 30 min for the tests, and three times 45 min for the intervention) was conducted over the course of three weeks. The post-test was the same as the pre-test. The pre-tests and post-tests delivered qualitative and quantitative data. The qualitative data were coded by a research assistant, with the help of a coding scheme designed by the authors of this paper. In order to assess the interrater reliability, 40 tests were also coded by the first author of this paper. Cohen's Kappa was 0.96, which indicates an almost perfect match.

The effect size was computed for each test item and for each condition, by subtracting the average pre-test score from the average post-test score, and dividing it by the pooled standard deviation (Cohen, 1988). Only those students who conducted the pre-test, intervention, *and* post-test were included in the data analysis.

6. Results

The experiment went well in both test groups. The teachers who conducted the lesson series with geospatial technologies spend just as much time on the topic as teachers who conducted the conventional lesson series: three lessons.

No technical problems occurred in the experimental group. Students played the game attentively and enthusiastically, and completed each module in about 20 min. However, there were some within-group differences when the students worked on the assignments after the game. While some students neatly made every assignment, other students had more problems staying focused. Differences between students were also noticed during the EduGIS lessons. While some students followed the assignments step-by-step as intended, others deviated from the planned route and explored the digital map by themselves. At the end of each lesson, about half of the students had completed all assignments. The teachers argued that this was quite normal, and that similar within-group differences regarding students' engagement in the tasks were noticed in the control group.

The pre-test data showed a slightly higher average score for the experimental group ($X = 31.8$, on a 0 to 100 scale), than for the control group ($X = 31.3$). The Effect Size (ES) was just +0.03, and a *t*-test showed that this difference was not significant ($p = 0.29$). Also, there were no differences between boys and girls on the pre-test scores ($p = 0.55$, ES = 0.00). However, the VWO classes (Pre-university Secondary Education) scored significantly higher on the pre-test than the HAVO classes (General Secondary Education), in both the experimental condition ($p = 0.0009$, ES = +0.43), as well as the control condition ($p = 0.0007$, ES = +0.41). As both conditions had the same number of VWO classes and HAVO classes, the difference between the two types of classes did not affect the outcomes of the study.

Analysis of the pre-test and post-test data showed that the lesson series with geospatial technologies had positive effects on students' achievement. In the experimental group, the average scores changed from 31.8 (on a 0 to 100 scale) in the pre-test, to 38.7 in the post-test (Table 3). The overall effect size was +0.38. This falls in the 'low to moderate practical significance' range according to Cohen's (1988) convention for interpreting effect sizes. The effect size was higher for the lower complexity assignments (on average +0.52) than for the higher complexity assignments (on average +0.25). Students especially improved their scores on task 5, which was a lower complexity

Table 3
Average standardised pre-test scores (*X1*), post-test scores (*X2*), and Cohen's *D* (effect size) for the experimental condition: the lesson series with geo-ICT ($N = 139$).

Item	Skill	Com-plexity	Pre-test score		Post-test score		*D*
			X1	*Stdev1*	*X2*	*Stdev2*	
1	Identifying non-spatial relationships in representations	Low	38.3	23.3	47.4	23.3	+0.39
2	Identifying geospatial relationships in geospatial representations	High	11.3	11.5	15.0	12.9	+0.31
3	Organizing geospatial relationships	Low	62.9	18.1	66.8	18.3	+0.22
4	Organizing geospatial relationships	High	28.1	19.0	32.5	19.9	+0.23
5	Evaluating measures and creating solutions	Low	37.1	16.3	53.4	18.2	+0.94
6	Evaluating measures and creating solutions	High	13.1	17.4	17.1	20.4	+0.21
Total			31.8	17.6	38.7	18.9	+0.38

design task that assessed skills in the category 'evaluating measures and creating solutions' ($d = +0.94$). For the other test items, the effect size ranged between +0.21 and 0.39. The effect size was slightly higher (ES = +0.05) for boys ($N = 71$) than for girls ($N = 68$), and slightly higher (ES = +0.04) for VWO classes ($N = 83$) than for HAVO classes ($N = 56$). However, these effects were not significant ($p < 0.01$).

In contrast to the lesson series with geospatial technologies, the contribution of the conventional lesson series to students' relational geographic thinking was minimal: the overall effect size was just +0.04 (Table 4). However, the data did show a small learning effect for the lower complexity CVS task with the paper planes (ES = +0.24), which suggest a learning effect from the test. The data of the control group also showed a small learning effect for the lower complexity design task in which students had to evaluate measures and create a solution for water-related challenges in a fictive delta (ES = +0.20), although the learning effect was much smaller than in the experimental group. The small learning effect does indicate that students had learnt about the functioning of the water system in deltas from the lesson series with the schoolbook. However, the data showed no learning effects for higher complexity relational thinking tasks (ES = −0.01 to −0.08).

A *t*-test conducted on the change scores showed that there was a statistically significant difference between the experimental group and the control group ($p < 0.01$). The difference in effect size between the experimental group and the control group was +0.34. This suggests that the lesson series with geospatial technologies contributed more to the development of geospatial relational thinking than the conventional lesson series.

Not only did the lesson series with geospatial technologies result in higher achievement, but students were also more positive about the effects on the learning outcomes. The survey data showed that students' perceptions about their knowledge about the water system increased in both conditions (Tables 5 and 6), but that the effect size was higher for the students in the experimental group ($d = +0.58$ to +0.68) than for students in the control group ($d = +0.26$ to +0.49). Although the two lesson series covered the same content, students who followed the lesson series with geospatial technologies had the feeling that they constructed more knowledge than students who followed the conventional lesson series. The teachers were also more positive about the lesson series. Four of the six teachers who participated in the research agreed that the learning goals and design of the lesson series with geospatial technologies were more closely aligned with the key tenets of modern geography education than the conventional lesson series (Table 7).

7. Conclusion and discussion

The findings of this study suggest that geography education with geospatial technologies can have positive effects on students' geospatial relational thinking. Students who followed a lesson series about water-related spatial planning issues with the Watermanager and EduGIS showed higher achievement on a geospatial relational thinking test than students who followed a conventional lesson series with a school book that focused on the same content. The effect size of the experimental condition ($N = 139$) was 0.34 higher than the effect size of the control condition ($N = 148$). This indicates a 'low to moderate' positive effect, which is quite promising, given the fact that the lesson series consisted of only three lessons of 45 min. Students who followed the lesson series with geospatial technologies were also more positive about the effects on the learning outcomes. This is good news for geography teachers who are thinking about introducing geospatial technologies in their classes, as the study suggests that at least some of the learning goals of geography education can be reached by using geospatial technologies.

Indeed, it may seem obvious that the post-test scores were higher for students in the experimental group than for students in the control group, as the lesson series with geospatial technologies paid more attention to systematic geospatial relational thinking. This is because it is difficult to develop lesson series for control groups and experimental groups that meet all of the following criteria: (1) the lesson series of the experimental group make use of the benefits of geospatial technologies as much as possible; (2) the lesson series of both test groups are realistic for the educational context; and (3) the lesson series of both test groups are comparable regarding the knowledge and skills that are trained. In this research, it turned out to be impossible to develop realistic analogue versions of the tasks in which students used the interactive technologies. Therefore, we decided to use an existing schoolbook lesson series in the control group that covered the same issues.

Still, this study showed that the lesson series with the Watermanager and EduGIS provided only a first step in realising deep geospatial relational thinking. In the experimental group, the average pre-test scores increased from 31.7 points to 38.7 points, which is still far below the maximum possible score of 100 points. Students identified only a part of the relations in the representations. Also, they were able to structure their knowledge about geospatial systems to a limited extent, and they took only a part of the relevant factors into account when they evaluated measures and sought solutions for spatial challenges. Why did their skills not increase more? First of all, geospatial relational thinking is a complex way of thinking. Research by Assaraf and Orion (2004) on earth systems thinking has shown that earth systems thinking skills can be taught, but that it takes a considerable amount of time: several tens of lessons. The same probably applies to geospatial relational thinking. Although it takes a considerable amount of time, we think that geospatial relational thinking is a goal worth pursuing, as it is such an important way of thinking for studying the challenges in the world around us. The second explanation for the lower-than-desired learning outcomes might be related to the design of the lesson series. During the tests, it seemed as if the tasks worked out well for a large part of the students, but not for all students. Some students followed the tasks better than other students. It seems likely that the

Table 4
Average standardised pre-test scores (*X1*), post-test scores (*X2*), and Cohen's D (effect size) for the control condition: the conventional lesson series ($N = 148$).

Item	Skill	Com-plexity	Pre-test score		Post-test score		*D*
			X1	*Stdev1*	*X2*	*Stdev2*	
1	Identifying non-spatial relationships in representations	Low	34.3	20.1	39.3	21.9	+0.24
2	Identifying geospatial relationships in geospatial representations	High	10.3	9.7	10.2	10.0	−0.01
3	Organizing geospatial relationships	Low	63.5	19.5	60.6	19.9	−0.15
4	Organizing geospatial relationships	High	28.9	18.2	27.9	17.8	−0.08
5	Evaluating measures and creating solutions	Low	37.0	15.4	40.6	19.6	+0.20
6	Evaluating measures and creating solutions	High	13.4	17.9	12.6	15.9	−0.05
Total			31.3	16.8	31.9	17.5	+0.04

Table 5
Average values for the survey question: 'How do you perceive your knowledge about the water system in the Delta Region and River Region (on a 1 to 5 scale)?' in the experimental condition.

Knowledge about the:	Pre-test score			Post-test score		
	N	*X1*	*Stdev*	*X2*	*Stdev*	*d*
characteristics of the water system	139	2.9	1.1	3.6	0.9	+0.68
functioning of the water system	139	2.7	1.1	3.4	1.0	+0.65
problems of the water system	139	2.8	1.0	3.3	1.0	+0.58
the water system (total)	139	2.8	1.0	3.3	1.0	+0.64

Table 6
Average values for the survey question: 'How do you perceive your knowledge about the water system in the Delta Region and River Region (on a 1 to 5 scale)?' in the control condition.

Knowledge about the:	Pre-test score			Post-test score		
	N	*X1*	*Stdev*	*X2*	*Stdev*	*d*
characteristics of the water system	148	2.9	1.2	3.2	1.2	+0.26
functioning of the water system	148	2.7	1.2	3.2	1.1	+0.49
problems of the water system	148	2.9	1.1	3.2	1.1	+0.26
the water system (total)	148	2.8	1.0	3.3	1.0	+0.34

effectiveness depends on students' learning style. If this is the case, we might need to redesign the tasks, or to differentiate the tasks, in order to optimize the learning outcomes. However, little is known about how students learn when they work on lesson series with geospatial technologies that aim to stimulate geospatial relational thinking. As far as we know, no process-oriented research has been conducted that connects learning styles, design of lesson series with geospatial technologies, and learning outcomes for particular geographic thinking skills. Therefore, we recommend investigating this issue further.

The potential of geospatial technologies has been widely recognised in the literature (e.g. Baker & White, 2003; Hall-Wallace & McAuliffe, 2002; Kerski, 2003; Milson et al., 2012; Sinton & Lund, 2007; West, 2003), but concrete evidence is still needed, especially when it concerns the effects on thinking skills, such as geospatial relational thinking. This study adds to the knowledge body about the effects of geography education with geospatial technologies. The difficulty with this kind of research is, however, that higher achievement cannot be attributed to the geospatial technologies alone. It is not the technology itself that produces learning, but the complex whole of clear and appropriate learning goals, solid educational technologies, well-designed tasks, and high-quality instruction, coaching, and reflection provided by the teacher. In this research, we have tried to optimize the output of the lesson series with geospatial technologies in several ways. First, we set clear learning goals: relational geographic thinking. Second, we chose two kinds of interactive technologies that are especially suited for exploring relations. Third, we designed tasks based on a theoretical framework for relational geographic thinking, in which students were stimulated to make relations explicit, both verbally (in the form of generalizations and rules) and visually (in the form of a conceptual framework). Fourth, and finally, we tried to stimulate teachers to set up an evaluative classroom discussion at the end of the lessons in which students had to summarise what they had learnt regarding the content and problem-solving strategy, although the degree into which they actually did so varied greatly among the teachers who participated in the project. As all components (learning goals, software, tasks, coaching, etc) are connected to each other, it would not make sense to try to attribute the positive learning effect to these components individually.

Lesson series without geospatial technologies that meet the same criteria (clear and appropriate learning goals, well-designed tasks, and high-quality instruction, coaching, and reflection) can also result in higher learning outcomes. However, without technologies such as the Watermanager and EduGIS, it would be much more difficult to develop a good lesson series about water-related challenges that aims to stimulate geospatial relational thinking. As the applications provide access to huge amounts of digital geographic information and contain interactive tools for investigating geographic relations, students can explore water-related problems deeply, in a way that is not possible with analogue materials. We therefore underline Palladino and Goodchild's (1993) argument that geospatial technologies make it easier to engage students in 'higher order thinking activities that are often so hard to come up with', and we think that geospatial technologies hold many possibilities to make a step towards education that focuses on deep learning. Unfortunately, in many countries, geography education focuses on learning facts and concepts and can be described as an ocean wide but just a few centimetres deep. Today, inquiry projects and systems thinking do not get as much attention as they should. Like Hattie (2009, p. 28), we think that a balance of surface and deep learning helps students to construct defensible theories of knowing and reality more successfully.

Table 7
Scores for the survey question 'Compare the lesson series with geo-ICT with the lesson series with the school book. How do the learning goals of the lesson series fit with the key tenets of modern geography education?'

	Frequency
The lesson series with the school book fits better	0
The lesson series with the school book fits slightly better	0
The two lesson series fit equally	2
The lesson series with geo-ICT fits slightly better	3
The lesson series with geo-ICT fits better	1

Nevertheless, using geospatial technologies is not always easy for students. The huge amount of geographic information and the interactive tools can only be an advantage for students whose actions are guided by good research questions. Also, students have to be able to investigate the challenges in the world around us in a systematic way, and be able to use the tools in a sensible way. Geography education with geospatial technologies should therefore follow a step-by-step approach, giving attention to the development of subject knowledge, inquiry skills, thinking skills and motivation. Teachers should provide feedback on the learning process, and organize whole class discussions on the content (Favier & Van der Schee, 2012).

The introduction of geospatial technologies in classrooms often requires extra effort for teachers (Kerski, 2003). However, the lesson series that was tested in this study did not require many technical skills, as simple applications were used. The teachers who participated in the study were able to use the applications without any technical training. However, in order to provide good feedback on the learning process, and in order to organize a good whole-class discussion at the end of the lessons, the teachers did need a considerable amount of knowledge about the water systems in the two regions, and did need to be able to help students structure their geographic thinking. So, in order to conduct the lesson series with *The Water Manager* and *EduGIS* in an optimal way, teachers especially need to increase their Content Knowledge and Pedagogical Content Knowledge, and not so much their Technological Knowledge and Technological Content Knowledge. As it was the first time that the group of teachers had used these applications and coached students in undertaking tasks that aim to structure students' geospatial relational thinking, it is no surprise that some teachers were better able to provide good feedback on the learning process and organize a good whole-class discussion than others. It would therefore be worthwhile to repeat the experiment with more experienced teachers, and see what the effect is. As the lesson series with geospatial technologies was very short, it covered only a part of the wide range of geospatial relational thinking skills, and did not practice these skills extensively. Furthermore, the lesson series could make use of only a part of the several advantages of geospatial technologies for stimulating students' geospatial relational thinking. Nevertheless, the results are very promising, and we recommend that this issue should be investigated further in a large-scale test, with longer lesson series, perhaps spread out over several years, that cover the entire range of geospatial relational thinking skills and practice these skills extensively, thereby making use of every advantage provided by geospatial technologies. Also, following Lee and Bednarz (2009), we suggest that much more research should be done on the learning effects of geography instruction on other components of geospatial thinking, and on how proficiency the different components of spatial thinking are related to teach other. Therefore, this study al least justifies the further pursuit of research in this field.

Acknowledgements

The authors of this paper would like to thank Anneke Kleeven, research assistant, for coding 600 tests.

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