

Investigating Web Mapping's Contribution to Students' Learning of Geographical Thinking

Julien Bachmann
University of Lausanne
julien.bachmann@unil.ch

Christian Kaiser
University of Lausanne
christian.kaiser@unil.ch

Research on the use of online maps in geography education underlines their potential to foster geographic thinking. However, the role of interactivity in this process has not been considered in educational settings. To address this issue, the contribution of web mapping to students' taxonomy is investigated. Our methodology combines analysis of student productions, mouse tracking, spatiotemporal clustering, statistical modeling, and focus groups. The data collection was carried out in three stages in a class of 20 students aged 14–15 years, using three online mapping interfaces with similar interactive features. Students' productions were evaluated using scores based on criteria constructed from Bloom's revised taxonomy to analyze their learning. Students' scores were compared to the way they interacted with the online maps. Results show how students master the tool over time. Temporal and spatial patterns of interactive behavior, and their impact on learning, were evident. Several of the cartographic interactions that we studied—such as spatial navigation and the display layer of attributes—had a positive impact on student learning when used moderately and intermittently, whereas juxtaposition only contributed positively when used occasionally. Focus group analysis complemented and contextualized our results by highlighting other factors such as students' emotions and their issues in interpreting the maps. As a result, we consider this exploratory research to provide an appropriate and useful methodological combination for further research into how digital tools contribute to learning.

KEYWORDS: web mapping; interactivity; geovisualization; learning; geography education; statistical learning; geographical thinking; mouse and map tracking

INTRODUCTION

GEOSPATIAL TECHNOLOGIES (GSTs), SUCH AS ONLINE mapping, are now widely available in various media (tablets, computers, smartphones) and are used in many contexts with practices resulting from the development of Geoweb 2.0 (Mericskay 2016). The growing number of resources for consulting and producing geographic information online reinforces the need to educate students on issues related to map interpretation and geographical thinking.

Web mapping is one of a number of digital technologies that are transforming teaching and learning practices in the school environment, though the progress of this digital transformation varies depending on the country and the institutional constraints. Research on the implementation of digital mapping (GIS or web mapping) in

schools highlights the potential of these tools to support the learning of geographical thinking by suggesting appropriate uses and underlining the role of context (De Miguel González and De Lázaro Torres 2020; Favier and van der Schee 2014; Jadallah et al. 2017; Jo et al. 2016). However, studies on the use of GSTs in geography education (from elementary school to university) do not address in depth how *interactivity* might influence the learning of geographical thinking. And yet, the interactivity of these digital tools is one of the key features that may influence the learning process.

Interactivity in geovisualization refers to the different ways of presenting information to a user within an interface, in response to that user's choices (Crampton 2002; Edsall et al. 2009). According to Roth (2012), *cartographic*



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interaction refers to the dialogue between a user and a web map through a computing device.

Interactivity is a key parameter which conditions learning by allowing users to explore, analyze, and synthesize (MacEachren 2004). It enables students to grasp the complexity of geographical phenomena, and contributes to knowledge generation and decision-making by encouraging thinking based on the creation and confrontation of hypotheses with the help of visualization (Çöltekin et al. 2018; MacEachren et al. 2004). In the research field of geovisualization, interactivity has long been a focus of study (Andrienko et al. 2010; Çöltekin et al. 2018; Çöltekin et al. 2017; Crampton 2002; Krygier et al. 1997; Roth 2012) and its impact on cartographic interpretation and knowledge construction remains a central research issue requiring further investigation (Roth et al. 2017). But, to our knowledge, no research has focused on the school context. As a result, the case study we present here investigates the following research question: How might web mapping contribute to the learning of geographical thinking through interactivity?

One of the concerns related to the implementation of these interactive tools, which has been identified as an obstacle

both in the literature and by teachers, is technical mastery: efficient use of the interactivity of online maps requires technical skills. Although many studies have demonstrated the potential of these tools at school, the changing influence of this parameter over time needs to be analyzed. Our two research hypotheses, which take this into consideration, are:

- H1. The technical ability required to use online mapping tools does not hinder student learning progress.
- H2. Interactivity contributes to students' geographical thinking by fostering the mobilization of higher cognitive processes.

In this article, we investigate our research question and hypotheses through a combination of mouse and map tracking, analysis of students' productions, and focus groups. Our aim is to illustrate how the use of different types of interactions is not a hindrance to learning, but is in fact likely to contribute to the learning of geographical thinking through map interpretation. We also explore how these interactions mobilize different cognitive processes and types of knowledge, as defined by Bloom's revised taxonomy.

GEOSPATIAL TECHNOLOGIES AND GEOGRAPHY EDUCATION

THE INTRODUCTION AND DEPLOYMENT OF GEOSPATIAL technologies—including virtual globes, remote sensing, and WebGIS—in geography education is driving changes in teaching and learning practices (De Miguel González and De Lázaro Torres 2020; Favier and van der Schee 2014). Geospatial technologies provide a new way of addressing geographic issues while working on students' spatial skills and geographic knowledge (De Miguel González et al. 2019). The use of WebGIS in place of desktop GIS has reinforced this trend (Kerski and Baker 2019). Empirical studies claim that the features and functions of these geospatial technologies meet the needs of the investigative and problem-solving approaches that are increasingly popular and widespread in education. In addition, such geomedia contribute to student motivation and interest while fostering spatial skills and geographical thinking (De Miguel González and De Lázaro Torres 2020; Jadallah et al. 2017; Jo et al. 2016; National Research Council 2006). Geospatial technologies can also play a significant role in learning and teaching during

fieldwork, while supporting group work and thus peer learning (Holloway et al. 2021).

Originally available as desktop software, GSTs are now also accessible on smartphones and tablets. These applications are used for field trips in the earth sciences (Fletcher et al. 2022; Lundmark et al. 2020), as well as projects in human geography, such as the collection of data for narrative mapping (Holloway et al. 2021). However, GST usage itself does not contribute to learning. To achieve this, the use of GSTs must be paired with geographic knowledge mobilization activities (Metoyer and Bednarz 2017). It should also be noted that these tools are not the only way to learn spatial skills and spatial reasoning (Jadallah et al. 2017).

Despite the advantages of GSTs (accessibility, multi-device use, adaptability to educational approaches, interface flexibility, user-friendliness) several limits may hinder GST use and require consideration. The technical

ability of students and instructors to handle these technologies remains a persistent constraint, despite the use of less-technical WebGIS instead of desktop GIS. Teachers and learners can also be reluctant to use GSTs. Some of them are not inclined to change their current habits due not only to potential difficulties in handling these digital tools but also to their own negative preconceptions.¹ The training time required for teachers and students to familiarize themselves with these tools may be a hindrance to their implementation, efficient use during activities, and student learning. Our observation in classrooms and with (future) teachers, as well as the literature, confirm these limitations (De Miguel González and De Lázaro Torres 2020; Holloway et al. 2021; Hong 2017; Walshe 2017).

Research in geography education highlights the potential of tools such as virtual globes and online GIS to support learning geographical thinking (Baker et al. 2015; Kerski and Baker 2019; National Research Council 2006; Schulze 2021), but most of these studies have been carried out with university students (Holloway et al. 2021). There are also research initiatives at the secondary school (De Miguel González and De Lázaro Torres 2020) and high school levels (Healy and Walshe 2020). However, few studies are devoted to elementary schools (Jadallah et al. 2017) or to teacher education (Walshe 2017).

GEOGRAPHICAL THINKING & MAP INTERPRETATION TAXONOMY –

GEOGRAPHICAL THINKING RELIES ON SPATIAL thinking (Metoyer and Bednarz 2017). Spatial thinking is a combination of three cognitive skills: using tools of representation, knowing concepts of space, and applying processes of complex reasoning (National Research Council 2006). Geographical thinking involves geographical knowledge related to the concept of space and is exercised, with the help of spatial thinking, to solve geographical problems (Metoyer and Bednarz 2017). Geographical thinking can, for example, consist in identifying and explaining a spatial distribution by linking it to social and economic factors.

Learning is defined here as a process and a product which combines mediation and cognition. Cognition refers to all intellectual information processing activities and their products (Vienneau 2017) including “internal mental

In these studies dedicated to geography education, GSTs are used within the fields of human and physical geography. They use a range of research designs and methodologies, including surveys, criterion-based production analysis such as the Learning Progression Model from De Miguel González and De Lázaro Torres (2020) and spatial ability tests: Spatial Thinking Ability Test (Jo et al. 2016) from Lee and Bednarz (2012), Cognitive Ability Test (Jadallah et al. 2017), spatial visualization and orientation skills and spatial relations content (Metoyer and Bednarz 2017). Focus groups are also employed to underline the contribution of these tools to geographical thinking. Nevertheless, these studies do not take into consideration the potential involvement of interactivity, despite it constituting a fundamental feature of the investigated tools such as WebGIS.

Roth (2013) highlights the need for further investigation of the contribution of interactivity to the visualization of geographic information and by implication to knowledge construction. Yet, to date, the role of interactivity on student learning has not been the subject of research in geovisualization. Therefore, in this article, we intend to examine the impact of interactivity on teaching geography in a secondary school (i.e., students aged between 12 and 15).

structures and processes involved in perception, attention, thinking and reasoning, learning, memory, and linguistic and nonlinguistic communication” (Montello 2009, 1824). Learning is also characterized by interactions between the learner and their environment which are mediated by tools or humans and are supported by cognition. As a result, mediation refers to the action of a tool or a human in the process of learning (Vienneau 2017). In this study, the learning of geographical thinking is evaluated during the process of map interpretation. From our perspective, map interpretation is a cognitive process in which the map has a mediation role during learning. Map interpretation is related to the features of both the map and the reader. A number of parameters may influence this process, such as semiotics, the projection system, perception and visualization, the reader’s cognitive abilities, and their emotions (Montello et al. 2018).

1. They may believe that Wi-Fi performance in their schools is not sufficient for using digital tools, or that planning digital activities will be too time-consuming.

Map interpretation Cartographic Language		The Knowledge Dimension				Major Types of Knowledge (KN)
		KN1 Factual knowledge	KN2 Conceptual knowledge	KN3 Procedural knowledge	KN4 Metacognitive knowledge	
The Cognitive Process Dimension	CG1 Remember	Learn	Obtain information	Articulate	Connect	<p>KN1 : The basic elements students must know to be acquainted with a discipline or solve problems in it.</p> <p>KN2 : The interrelationships among the basic elements within a larger structure that enable them to function together.</p> <p>KN3 : How to do something, methods of inquiry, and criteria for using skills, algorithms, techniques, and methods.</p> <p>KN4 : Knowledge of cognition in general as well as awareness and knowledge of one's own cognition.</p> <p>Cognitive process (CG)</p> <p>CG1 : Retrieve relevant knowledge from long-term memory.</p> <p>CG2 : Construct meaning from instructional messages, including oral, written, and graphic communication.</p> <p>CG3 : Carry out or use a procedure in a given situation.</p> <p>CG4 : Break material into its constituent parts and determine how the parts relate to one another and to an overall structure or purpose.</p> <p>CG5 : Make judgments based on criteria and standards.</p> <p>CG6 : Put elements together to form a coherent or functional whole; reorganize elements into a new pattern or structure.</p>
	CG2 Understand	Learn	Obtain information	Articulate	Connect	
	CG3 Apply	Learn	Obtain information	Articulate	Connect	
	CG4 Analyze	Learn	Obtain information	Articulate	Connect	
	CG5 Evaluate	Learn	Obtain information	Articulate	Connect	
	CG6 Create	Learn	Obtain information	Articulate	Connect	

Knowledge dimensions and cognitive process retrieved from : KRATHWOHL, 2002.
Inspired by RAYNAL ET RIEUNIER, 2012, pp. 114-116 and adapted from : Bachmann, 2020.

Figure 1. Map interpretation taxonomy adapted from Bachmann (2020, 38).

In order to investigate learning in this context, we employed a map interpretation taxonomy (Bachmann 2020) based on Bloom's revised taxonomy (Anderson and Krathwohl 2001). Originating from the field of educational sciences, Bloom's revised taxonomy is used not only in research frameworks (De Miguel González and De Lázaro Torres 2020; Favier and van der Schee 2014; Schulze 2021) but also by teachers to evaluate and build students' learning. The use of Bloom's revised taxonomy was also inspired in part by Saint-Marc et al. (2017). They present the results of an experiment where mouse tracking is used and discuss the contextualization of their findings by employing cognitive processes identified in Bloom's revised taxonomy. This approach has been adapted to the needs of the current study, which consists in investigating the role of interactivity on learning with the help of a map, with mouse and map tracking being employed here to examine interactivity.

Criterion
C1: The student masters cartographic language.
C2: The student retrieves relevant information from the map.
C3: The student coherently links information from the map.
C4: The student problematizes information and relations generated from map interpretation by mobilizing his/her knowledge in a relevant and coherent way.
C5: The student identifies his or her difficulties in completing the task and how easy it was.

Table 1. Taxonomic score criteria.

We employed a map interpretation taxonomy to build activities and assess student performances. The definition of the levels of knowledge and cognitive processes mobilized during map interpretation are detailed in the Appendix (see Figure 1). Four components, in particular, stand out as related to map interpretation ability: master cartographic language, obtain information, connect, and problematize.

Each of these components was then transformed into a criterion (see Table 1) to analyze the students' productions and assign a taxonomic score. As shown in Figure 2, these criteria are based on different levels of knowledge and

cognitive processes. As a result, each question answered by the students allowed us to assess their mobilization of one or more levels of knowledge and cognitive processes defined in the map interpretation taxonomy. In summary, this taxonomy allows us to analyze the contribution of interactive cartographic features, i.e., the interactivity of the online maps used by the students, on the learning achieved according to the mobilization of cognitive processes and knowledge levels. For feasibility purposes in terms of data collection and analysis, metacognition was isolated and studied using a separate questionnaire after each activity.

TAXONOMIC SCORES Scores structured by cognitive process and map interpretation components (Bachmann, 2020)		The Knowledge Dimension			
		KN1 Factual knowledge	KN2 Conceptual knowledge	KN3 Procedural knowledge	KN4 Metacognitive knowledge
The Cognitive Process Dimension	CG1 Remember	C1 SCORE: MASTER CARTOGRAPHIC LANGUAGE			C5 SCORE: METACOGNITION
	CG2 Understand				
	CG3 Apply	C2 SCORE: OBTAIN INFORMATION			
	CG4 Analyze	C3 SCORE: CONNECT			
	CG5 Evaluate	C4 SCORE: PROBLEMATIZE			
	CG6 Create				

Figure 2. Taxonomic scores, based on Bachmann (2020, 38).

METHODOLOGY

IN THIS SECTION, WE DISCUSS THE RESEARCH DESIGN, data collection, and transformation of tracking data. Figure 3 summarizes all the procedures implemented and the materials collected: data on mouse cursor and map movements, students' productions, and focus groups.

RESEARCH DESIGN AND DATA COLLECTION

At the time of data collection, the use of digital technology, and in particular web mapping in the classroom, was uncommon in the teacher's school with which we partnered. The implementation of such geomedias in schools in general was in its early stages in the Canton of Vaud, in the French-speaking region of Lake Lemman, Switzerland, where the school was located. However, our partner teacher, also a teacher educator, had a strong interest in setting up innovative ways of learning which differed from

usual practices. He was involved in both economics and geography education in his school, supporting a cross-disciplinary approach in his teaching to highlight links between these disciplines while maintaining the stipulated curriculum.

The students in this study were between the ages of 14 and 15. They had been taught geography since elementary school and also as part of their secondary education. These students came from different classes and met together to study economics. As such, our sample (n = 20) included students who had experienced various teaching practices. They were using an online map for the first time in a classroom setting.

This class met several times a week in the fall and spring. This made it possible to collect data on several occasions

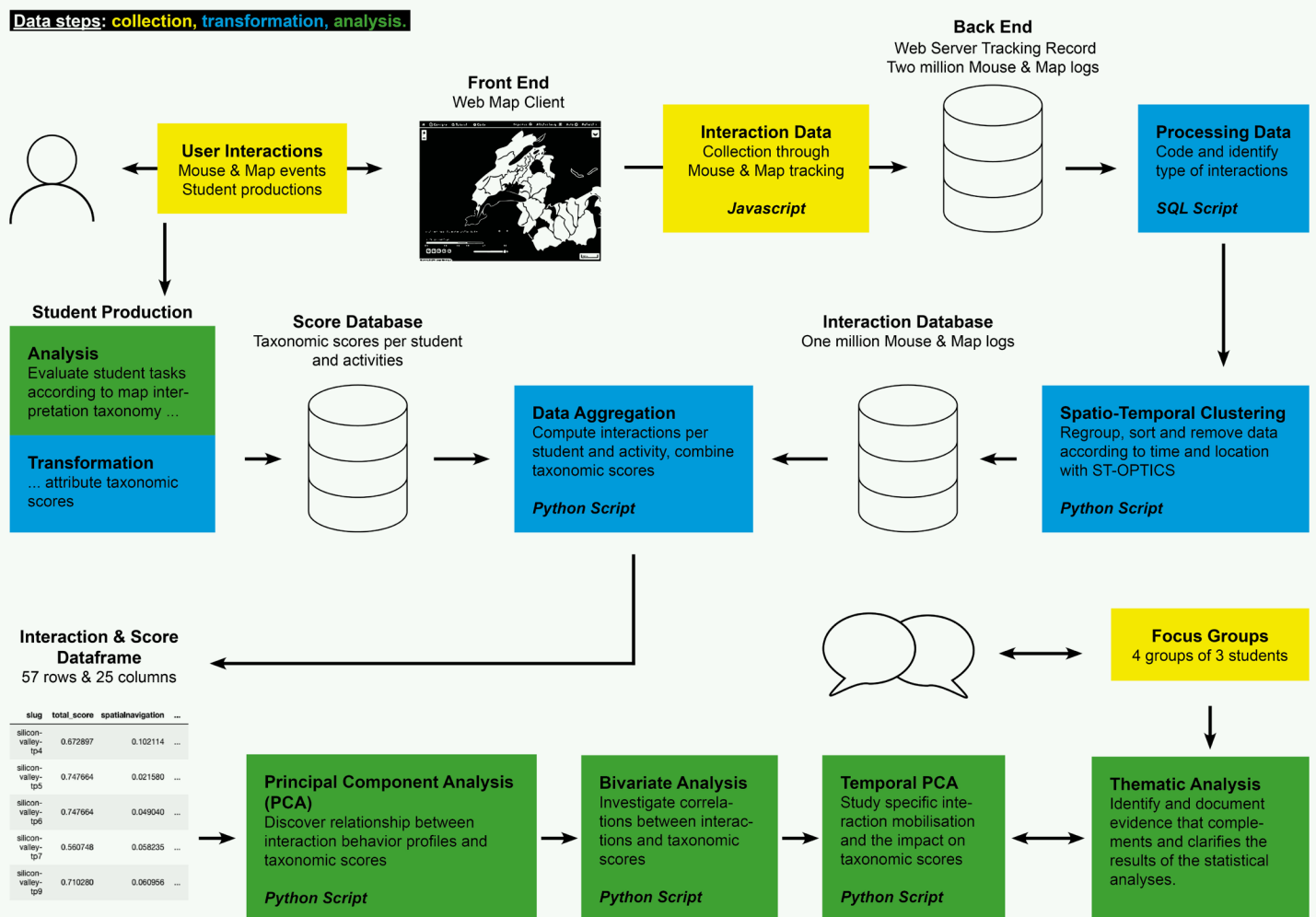


Figure 3. Data Collection Processing and Analysis Steps

and study how technical ability, and the effects of interactivity on learning geographical thinking, changed over time. We worked with this class while emphasizing geographical thinking in the activities and incorporating economics concepts. The data collection took place over three different activities between November 2020 and April 2021. The first activity focused on global trade, the second on Silicon Valley, and the last on commodity trading in Switzerland. Forty-five minutes (maximum fifty) were allocated to each activity. During these activities, students conducted an inquiry based on the above-mentioned themes. This investigation was based on questions to which the student provided answers using indicators and layers provided through an online map (Figure 4 shows an example).

Each of these questions was based on a taxonomic score (see Figure 2). Students' responses were then evaluated according to the criteria presented in Table 1. The meta-cognition score (C5) was collected separately. Students filled out a survey after each activity, with questions focused on their reflexivity about their learning. This refers

to their ability to identify their difficulties and their ability to carry out the activities critically and objectively, as well as their ability to implement strategies to overcome their challenges. The right side of Figure 4 shows the relationship between the questions and the taxonomic scores circled in red (C1, C2, C3, C4).

The sample activity shown in Figure 4 involved investigating features of Silicon Valley to discover why companies active in new technologies are located there. To this end, students could consult provided indicators (maps and histograms) for the year 2019 (average household income, employment in the information sector, employment in scientific and technical services, population with a bachelor's degree or higher) as well as layers on the Big Five tech firms, California universities, and the list of Silicon Valley counties. A neutral base map and an aerial view were available to the students.

All of these activities were carried out using a web mapping website specifically developed for this research. Each activity uses the same interface, with an identical

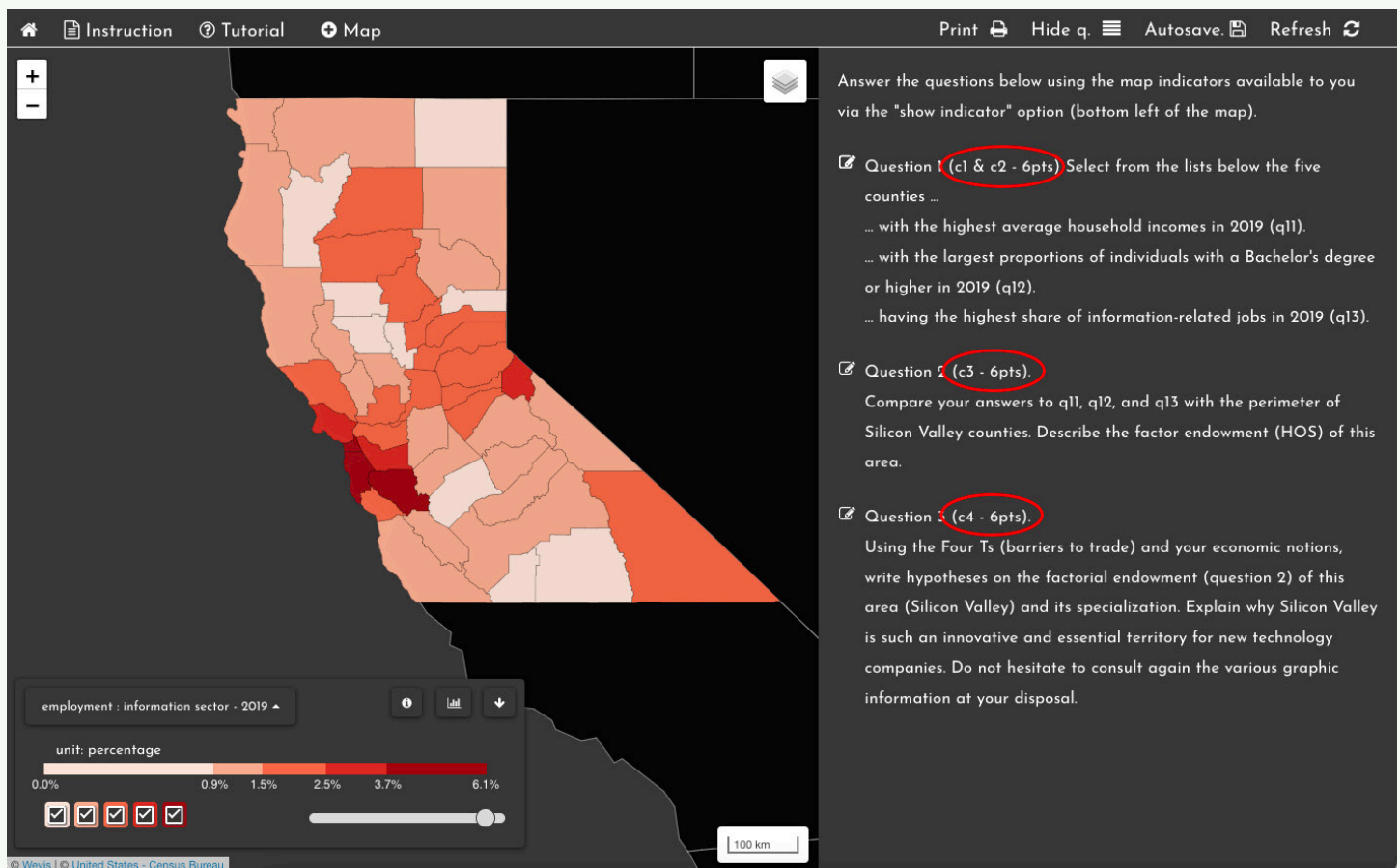


Figure 4. Silicon Valley web map.

KIND OF INTERACTIVITY	INTERACTION INDICATORS (present in all three activities)	FEATURES
Interaction with the data representation	spatial navigation	move on the map without modifying the perimeter and display the attributes of the indicator by mouseover
	spatial navigation zoom	zoom on the map
	spatial navigation move	change of map perimeter
	display layer attribute	displaying the attributes of an indicator (map or chart)
	edit layout	change the display of the data representation
Interaction with data	highlight	data highlighting
	load data	data selection and loading
Contextual interaction	juxtaposition	juxtaposition of layers or several indicators on the same or different map or via a chart
	exploration	display of the instruction, the tutorial, navigation outside the map and chart containers

Table 2. Interactivity and interactions implemented on the website.

cartographic background and interactive functionalities, as well as a set of questions built using the map interpretation taxonomy. Between the three activities, only the indicators and maps differed. These were produced according to themes chosen by the teacher. Various kinds of cartographic representations (choropleths, proportional symbols, colored proportional symbols) were implemented and evaluated by the students. Histograms and line graphs were also included. Different interactive graphical features were implemented to evaluate the contribution of these maps to the students' learning. The choice of these features was inspired by our own practice and experience, and can be theorized using previous work by Roth (2012) and Crampton (2002). Table 2 presents interactivity and interactions in all the three activities.

Two main issues had to be addressed during data collection: teaching and research adequacy, as well as uncertainty brought by the pandemic context. Firstly, data collection had to be carried out in the context of the teacher's program. Web maps were therefore developed to include specific cartographic indicators linked to teaching subjects. Secondly, only the teacher and the researcher were present during the activities with the students. It was thus

impossible to collect and supervise specific time-limited tasks as a classical laboratory setting. Furthermore, the aim was to obtain data that reflected the school environment and constraints.

MOUSE & MAP TRACKING COLLECTION AND TRANSFORMATION

To keep track of the students' interactions with these online maps, mouse tracking and map tracking were integrated into the online mapping site. For the last fifteen years, researchers in psychology and cognitive science have been using this technique to investigate the cognitive processes at work during an action involving significant contributions. Among other things, this method has been used to explore judgment and decision-making, social cognition, and language processing (Kieslich et al. 2019; Schoemann et al. 2021; Stillman et al. 2018; Wulff et al. 2019). The association between cognition and mouse tracking is derived from the assumption that cognitive processes determine the motor activity and consequently the movements of the mouse (Hehman et al. 2015; Spivey and Dale 2006).

We also implemented map tracking, which is the collection of coordinates recording the user's interactions with the map. This method of data collection is sometimes used in geovisualization (McArdle et al. 2015). However, eye tracking is a more widespread method than the combination of mouse tracking and map tracking to investigate how maps and interaction contribute to knowledge building and decision making (Çöltekin et al. 2010; Golebiowska et al. 2020; Ooms et al. 2014). Mouse tracking is sometimes employed as a complement to eye tracking to obtain additional information, but rarely by itself. These combinations of monitoring methods are mainly used in the context of evaluation and design of cartographic interfaces (Çöltekin et al. 2009; Ooms et al. 2015; Manson et al. 2012). Compared to map tracking, mouse tracking does not seem to have been widely used in geovisualization, but it provides some interesting information on how users interact with web maps.

Mouse and map tracking data were processed with spatio-temporal clustering (STC), which is used in spatial data mining to regroup data with similar location and temporal patterns. This process can highlight trends or patterns in databases with geographical coordinates—usually longitude and latitude. The cluster analysis used in this study was an unsupervised procedure that did not require a priori understanding (Ansari et al. 2020). Despite

the wide application of STC in the real world (Ansari et al. 2020), it has not, to our knowledge, been used to study digital media in schools.

Based on the nature of the data collected (mouse tracking and map tracking), event clustering was chosen. Event clustering allows the detection of similar groups of points, according to their spatial and temporal features, and even other features (Kisilevich et al. 2010). The ST-OPTICS method (Ankerst et al. 1999) was employed for its ability to detect clusters of varying density. Working with spatio-temporal data requires several steps before and after the clustering. First, data needs pre-processing to ensure validity and completeness. Then data mining, such as exploratory data analysis, is used to calibrate the algorithm (minimum sample and temporal interval). Approximately two million mouse movements and map events were collected. This sample was processed to identify all the different interactions. Then, spatio-temporal clustering was applied to eliminate noise and reveal clusters of points, which allowed us to discover interactivity behavior patterns as students interpreted the digital map. These transformations and selections resulted in a sample size of one million records. This large amount of data was transformed into one dataset with every student and activity ($n = 57$) and their use of interactivity.

RESULTS

THE FIRST PART OF OUR RESULTS RELIES ON STATISTICAL analyses. In this section we examine the relationships between interactions and taxonomy scores to assess the role of key parameters of our two hypotheses—technical ability and interactivity—and the evolution of their influence on the learning of geographical thinking over the three activities. We begin by describing the evolution of these variables over the three activities, followed by an investigation of the relationships between these variables using PCA and bivariate analysis. Then the results of the statistical analyses are complemented with data from focus groups.

STATISTICAL ANALYSES OF INTERACTIONS AND TAXONOMIC SCORES

The following data shows the evolution of all the scores and interactions. Around one million interactions were

analyzed. Based on the tracking recorder logs, a significant decrease of interactions (-96.6%) happened between the first (~576,000 logs) and the last (~18,000 logs) activity. Unsurprisingly, *spatial navigation* (41.97%) and *display layer attributes* (18.43%) were the most commonly employed interactions, as students were required to explore and interpret the map data to perform their tasks. Table 3 shows the interaction logs. As we will see later on in the statistical analysis (PCA and bivariate), interaction contribution to learning was not related to the mobilization percentages.

In each activity, students answered similar questions that focused on the same components of map interpretation (see Figure 2) and they were assessed with the same criteria (see Table 1). Mastery of cartographic language (C1_score) and information extraction (C2_score) were the least challenging for students, in contrast to

Interaction	Juxtaposition	Edit layout	Spatial Navigation zoom	Highlight	Load data	Spatial Navigation Move	Exploration	Display Layer Attributes	Spatial Navigation
Percent	1.30	1.31	1.78	5.26	5.56	8.06	16.33	18.43	41.97

Table 3. Interaction logs.

metacognition (C5_score), analysis (C3_score), and problematization (C4_score). Between the first and the second activity, all taxonomic scores increased. Analysis and problematization improved between the second and last activity. In summary, across all activities, the components of map interpretation that were most difficult for students (connect and problematize) displayed the largest average score increases (+2 and +2.38 points respectively). These results show that the students improved their mobilization of higher cognitive processes during the three activities, as suggested by one of our hypotheses. The next step in the

analysis was to identify the interactions that may promote the mobilization of these cognitive processes. The comparison and modeling of total interactions and scores per activity per student (Figure 5) reveals homogenization in terms of mobilization of interactivity. This trend is paired along with an interaction decrease and an increase in total score. It might be explained by a learning effect related to repeated similar activities. This highlights to some extent the importance of tool mastery and it reveals, by extension, the presence of technical ability.

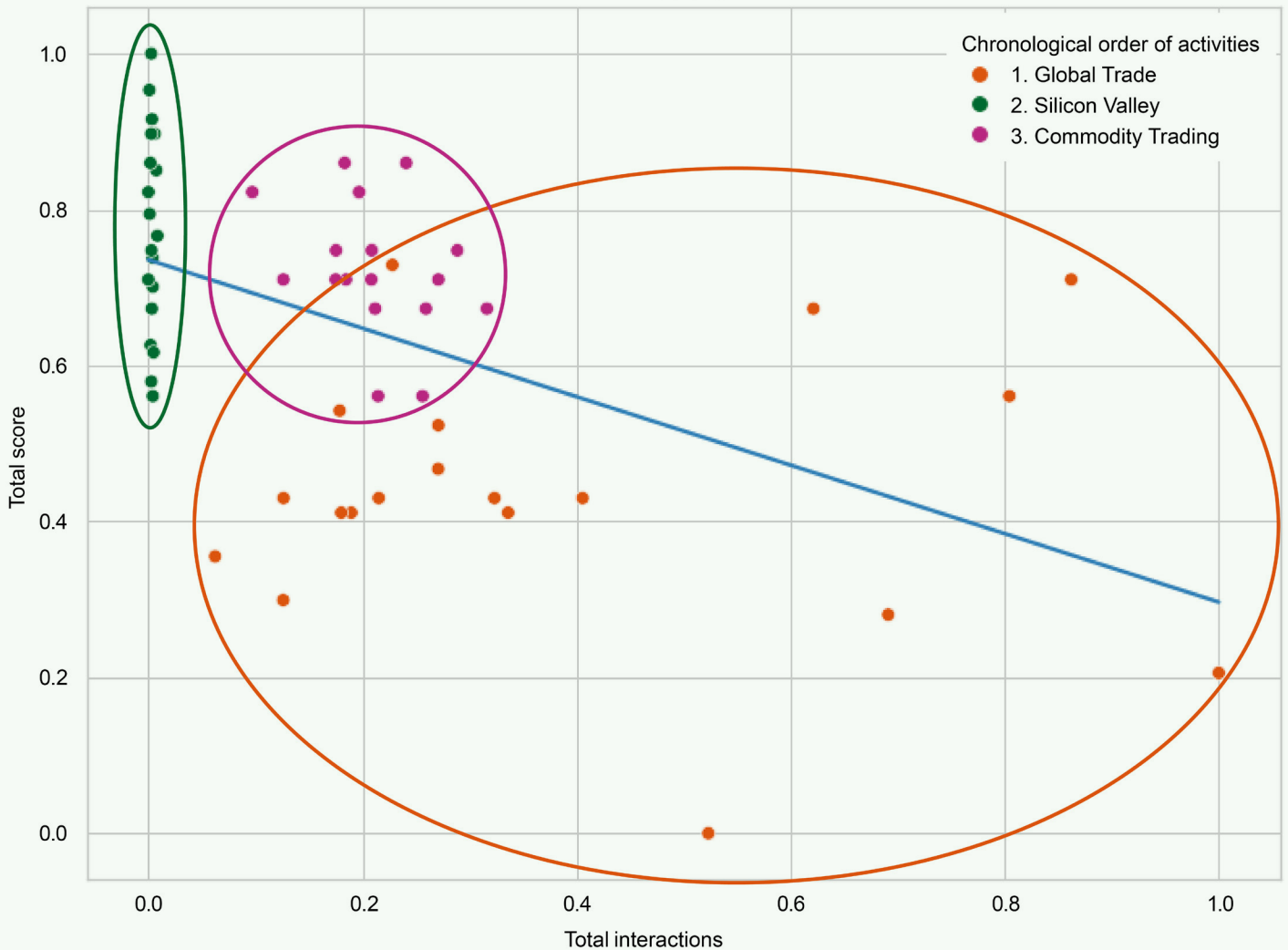


Figure 5. Interaction selection and taxonomic scores.

PC1: technical ability (45%). PC2: investigation and comparison factor (21%). PC3: synthesis ability (12%).

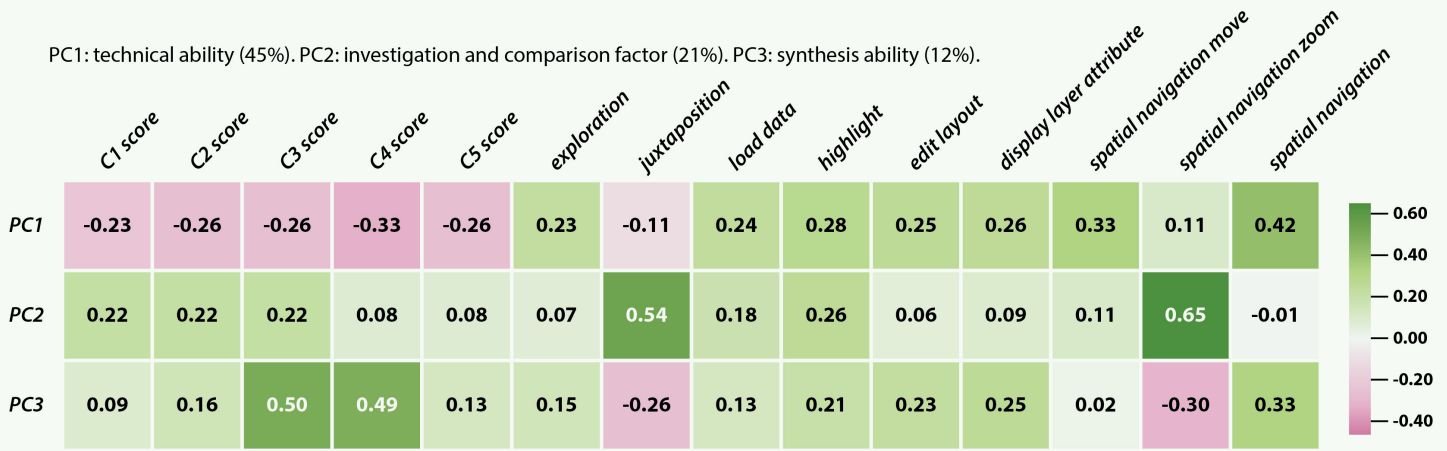


Figure 6. PCA correlation matrix.

We used principal component analysis (PCA) to examine the relationships between scores and interactions in depth. The goal here was to further discover the influence of interactivity on learning geographical thinking. PCA distinguished three factors related to students' interactive behaviors and learning using the interactive variables and taxonomy scores. These three factors summarized around 78% of the information in our sample. The examination of the correlation matrix in Figure 6 reveals the following factors:

1. **Technical ability** (45%) illustrates an effective use of the interactive features of the web mapping interface, with a positive contribution to learning. The positive values of the interactive variables (except *juxtaposition* and *spatial navigation zoom*) are opposed to the negative values of the scores. Therefore, the higher the use of the various interface features, the lower the taxonomic scores obtained.
2. **Investigation and comparison** (21%) is associated with searching, comparing, and linking information behavior. It is related to the following interaction indicators: the high mobilization of *spatial navigation zoom* and *juxtaposition*, and the slight use of *highlight*. These indicators had a moderate impact on several taxonomic scores: master cartographic language (C1), obtain information (C2), and connect (C3).
3. **Synthesis ability** (12%). This factor shows the influence of students' connecting and problematization abilities on the use of most of the interactive

features. *Juxtaposition* and *spatial navigation zoom* (the important variables of the second factor) are not included. As a result, it would appear that students with better analytical and synthesis skills use certain interactive features that allow them to link the characteristics of the cartographic indicators: *spatial navigation*, *display layer attribute*, and *highlight*.

The PCA results support the previously observed role of technical ability in modeling interactions and taxonomic scores. It also suggests that the contribution of interactivity to learning is likely to be related not only to the mobilization of one or more kinds of interactivity (featured in Table 2), but also to associations between these kinds. In addition, this PCA reveals the significant influence of the following interactive variables and taxonomic scores: *spatial navigation*, *spatial navigation zoom*, *juxtaposition*; connect (C3 score) and problematize (C4 score).

To study the changing role of technical skill, the related PCA factor was transformed into a variable, in order to analyze its influence over all taxonomic scores during the three activities, using bivariate modeling. Observing the evolution of the overall points in these three activities representing total scores and factor 1 (technical ability) indicates a distribution reduction in their perimeter over the activities (see Figure 7).

This probably reflects a dynamic of homogenization of behaviors over time: i.e., the adoption of interactive practices that lead to an increase in taxonomy scores that are more or less marked depending on the students. Modeling of PCA factor 1, technical ability, indicates a strong

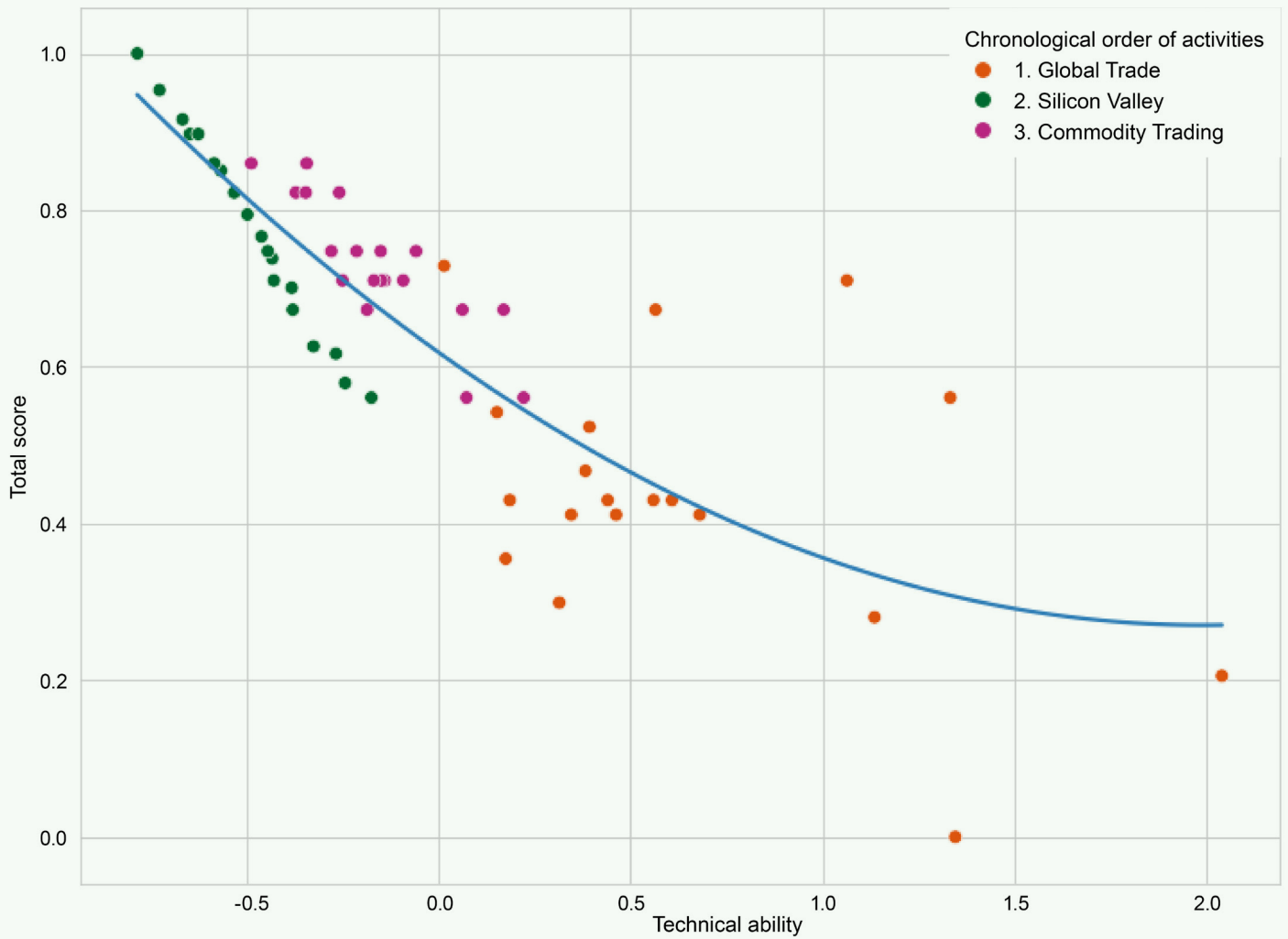


Figure 7. Non-linear regression of technical ability and taxonomic total score.

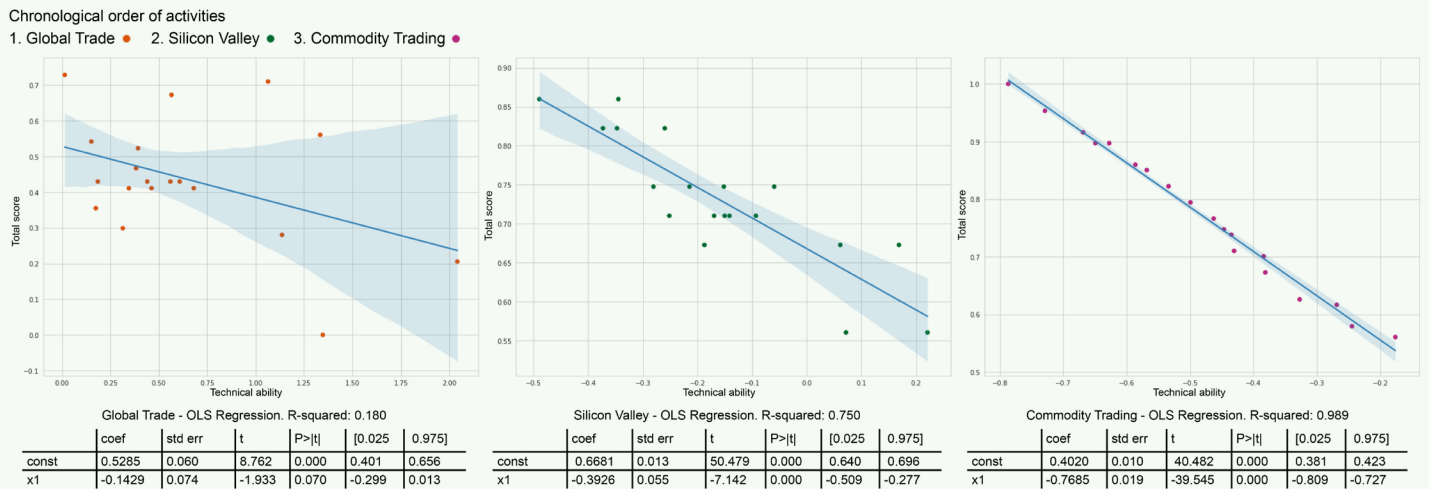


Figure 8. Linear regressions of technical ability and taxonomic total score per activity.

correlation (R^2) of 0.71. The distribution points out that a high mobilization of interactivity does not equal a high taxonomy score.

Separate modeling of the points from each activity indicates a decrease in the dispersion of the data with subsequent activities (see standard errors in Figure 8), as well as a clear reduction in the influence of technical skill on the taxonomic total score. This decrease is underlined by the values of the slopes of the linear regressions. In the first activity, we observe a significant dispersion. In the second activity, we observe the appearance of a significant negative correlation between the technical skill and the scores. Finally, in the third activity, the influence of the technical ability on the taxonomic total score decreases significantly.

Regarding problematization and connection taxonomic scores, the statistical correlation (linear regression) with technical ability is significant (R^2 of 0.71 and 0.52 respectively). All other taxonomic scores indicate a moderate R-squared correlation (~0.44). Therefore, the more a task mobilizes demanding cognitive processes and higher levels of knowledge, the more technical ability plays a preponderant role. However, as for the total taxonomic score, the same trend of reduction of this parameter's influence during the three activities is observed on the bivariate modeling of the taxonomic scores.

Endogenous	Exogenous	Degree of Regression	Coefficient(s)	R^2
total score	spatial navigation	2	-1.54, 1.29	0.49
total score	display layer attributes	2	-1.5012, 1.4259	0.37
total score	juxtaposition	1	-0.1818	0.36
total score	edit layout	3	-2.77, 7.8, -5.54	0.34
C4 score	juxtaposition	1	-0.25	0.39
C5 score	display layer attributes	2	-1.62, 1.45	0.37
C3 score	spatial navigation	3	-1.91, 1.78	0.37
C4 score	spatial navigation	2	-1.96, 1.73	0.37
C2 score	spatial navigation	2	-1.52, 1.32	0.35

Table 4. Bivariate analysis results (p-value < 0.05).

These results illustrate the evolving influence of technical ability on learning and partially confirm our first hypothesis (H1). At first, this parameter has some importance in the progression of learning, but its influence decreases considerably and disappears by the last activity. This finding indicates that technical ability to use an interactive map does not hinder student learning in our experiment.

The following analysis focuses on the second hypothesis (H2). It involves examining the role of interactivity in the mobilization of higher cognitive processes. Initially, we investigated all interactions mentioned in Table 2 to identify which may contribute to learning through taxonomic scores. As Table 4 shows, bivariate analysis (p-value < 0.05) reveals that the following interactions could have a moderate impact on the mobilization of higher cognitive processes, in order of importance and frequency: *spatial navigation*, *juxtaposition*, and *display layer attribute*. The selection of these interactions is conditioned to a value of the correlation rate higher than 35% in at least one model.

The next step in the analysis is to examine the mobilization of these interactions in time and space. In other words, it is a question of more precisely locating the parts of the interface that are mobilized and at what time and frequency. To conduct this analysis, we separated the interactions for each of the activities into time windows of 5 minutes each,

and applied a separate PCA to each of the interaction types with the time intervals as variables (these PCAs are referred to as temporal PCAs in the remainder of this text). The analysis was done simultaneously on all three activities, with the time starting at zero for each activity. Students had, at maximum, 50 minutes of time to complete each activity. The results of these analyses depict different behavioral profiles of the technical ability factor revealed during the initial PCA. The temporal PCAs of four of these interactions—*spatial navigation*, *display layer attribute*, *spatial navigation move*, and *highlight*—suggest that when they are mobilized in a moderate and intermittent

way throughout the activity, it has a moderate to significant positive impact on the scores and the mobilization of higher cognitive processes. The temporal PCA results of the *juxtaposition* interaction differ from those four however, in the temporal structure of the factors obtained. This interaction also contributes to supporting the activation of higher cognitive processes. Indeed, a slight mobilization of those processes would lead to a moderate impact on problematization and connecting. Our observations are summarized in Figure 9, which show interactive mobilization behaviors that contributed the most to student learning.

Examination by interaction and by score using bivariate modeling (Table 4) and temporal PCAs (Figure 9) underlines the prominent part played by specific interactions from the various kinds of interactivity (see Table 2) in the mobilization of the higher cognitive processes present in problematization (C4 score) and connecting (C3 score). Temporal PCAs highlight interactive behavioral patterns that imply higher taxonomic scores. These analyses bring evidence in favor of our second hypothesis (H2).

THEMATIC ANALYSIS WITH FOCUS GROUP

A focus group was assembled by selecting students according to their taxonomic scores, to obtain a panel composed of students with varied learning outcomes (5 girls and 7 boys). All participants voluntarily agreed to participate in the focus groups. Due to school-related constraints, only four twenty-minute focus groups were conducted, after the conclusion of all three activities. Each group consisted of three students, who responded unprepared to questions related to their experience with the three online maps. The questions (which can be found in the Appendix) concerned the role of interactivity in their learning, cartographic and

graphic interpretation (mobilization of taxonomic levels depicted in the map interpretation taxonomy), the difficulties encountered during the tasks, and how to overcome them (metacognition) such as mastering the web map interface. The focus groups also included a debriefing where students could express themselves freely. We chose thematic analysis to identify recurring themes in the students' comments (Hay 2005). A first coding grid based on the components of the map interpretation taxonomy, interactivity, and technical ability was used in our initial analysis. Following this initial analysis, other codes emerged and made it possible to identify other key themes related to task features and contexts.

From this analysis, we obtained information on the possible influence of technical ability and interactivity as well as other factors related to the progression of learning (H1) and the mobilization of higher cognitive processes (H2). These other factors reflect the context of the tasks and its role in learning geographical thinking. The purpose of these thematic analyses was to reveal and document evidence that complements and clarifies the results of the statistical analyses with student feedback.

The use of a web map as part of a teaching session was new to all students. A time of adaptation and initiation was therefore necessary. From the second activity, students claim to have understood how the site worked. This confirms the existence of the learning effect observed in one of the statistical analyses (see Figure 8) and underlines that technical ability is not a hindrance to learning despite the *school practices* discussed further.

Because I didn't really know how it worked, so I wasn't used to it. Instead of looking at the

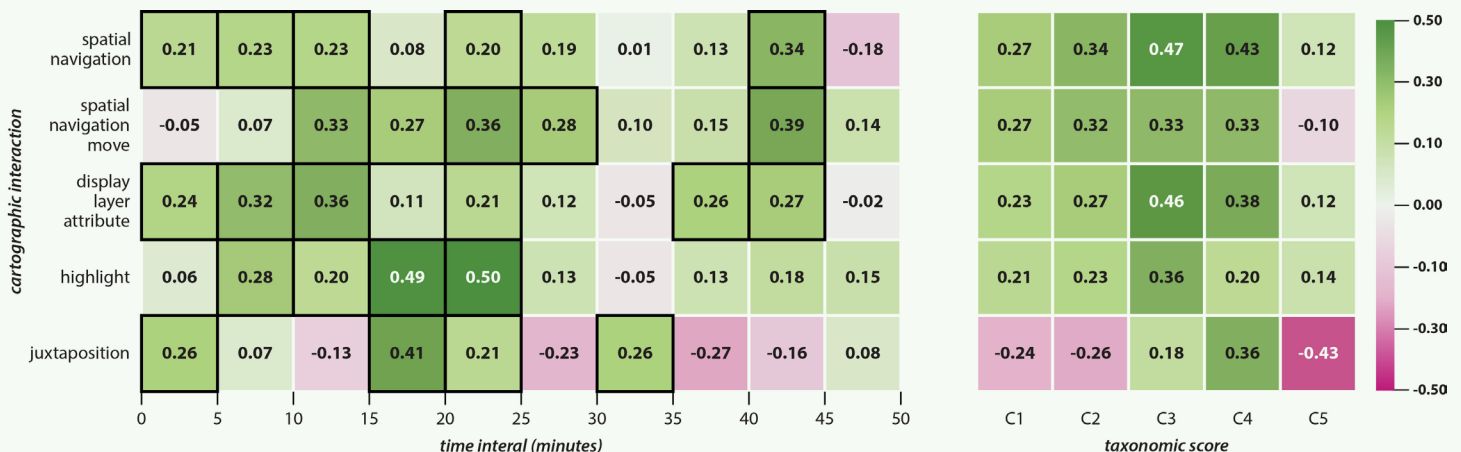


Figure 9. Interactive behaviors with the most contribution to learning.

questions, I tried to understand first, to see all the possibilities to see how it worked. Then, little by little, I started to use the graphics more and more. (Focus Group 4: Student 2)²

But I think, after [the first activity] I was more familiar with the website too, the way it works. (FG1: S2)

From the perspective of mobilizing interactivity, students mention different behaviors. Students took advantage of some interactive features to facilitate their work. One of these features corresponds to one of the cartographic interactions highlighted during the statistical analyses: the juxtaposition of two maps, which allows comparing and analyzing two cartographic indicators. Using this interaction, they were able to conduct analyses through comparisons.

I also liked the [double] maps very much, finally, because they allow you to compare two indicators, which is more practical than having to select one and look at the other all the time, because you can see both at the same time. (FG2: S1)

Other interactive features related to the other types of interactivity were mentioned, such as highlighting certain classes, and displaying the attributes of the indicators. All three kinds of interactivity (see Table 2) were used to perform tasks. *The combination of the three types of interactivity* is also a parameter to consider, as the first PCA revealed. The students' feedback reveals other factors that influenced learning and the mobilization of higher cognitive processes. The first is related to indicator representations. It is related to the *semiological and semiotic features of the graphic representation types* (maps, charts). Students encountered interpretive difficulties when graphic representations combined two pieces of information such as colored proportional symbol maps. Proportional symbol maps also generated abstraction barriers in terms of perceived size difference, but not unanimously. In the first two activities, students had access to scatterplots, a bar chart (Silicon Valley), and a line chart (global trade). In the third activity, only proportional symbol and choropleth maps were available. In the second activity, some students relied on the bar chart to answer the questions. The choropleth map was the representation most preferred by the majority of students. Its visual attractiveness could

affect its readability. Thus, the *visual aesthetic factor* may influence students' preference for this type of representation. Another one of the non-trivial factors in this type of school-based study is the role of *school practices* in relation to digital tools and maps. Students had not previously encountered the use of online maps in assessments.

Well, for me, it was the first time that I had ever done an exercise like that. I had never seen a digital map. So I had to take my time to see how it worked and all that. (FG1: S2)

But uh, it was really interesting and it was a change from what we usually do, we don't do this kind of thing often, it's tests that we have, assessments or we have to learn something by heart or we have knowledge that we have acquired during the courses and then we transcribe it, we transcribe what we have learned, etc. But here, we had a support that helped us answer certain questions. So it's a different approach from what we usually do and I think it's really cool. (FG4: S1)

The difficulty associated with this novelty was also amplified by the use of web maps to answer questions requiring analysis and synthesis skills. Students had never been confronted with this type of activity in class. They emphasized their difficulties in answering questions requiring an analysis of different information (connection component) and the creation of hypotheses (problematization component). These statements correspond to the evolution of the taxonomic scores mentioned. Nevertheless, some of them were very satisfied to be able to connect facts retrieved from map interpretation.

It also taught me that, well, first of all, I liked making links between things and that I find it interesting to be able to make links. And then, it will also improve, to put precisely as [S2] says, to make the links between the various, the cards and then the information which one knows, then the questions, then the logical things. Because we hadn't really had such a developed analysis of a question. (FG1: S1)

The *intellectual complexity factor* of these questions was likely reinforced by the lack of prior similar experiences.

2. The focus groups were conducted in French. The comments mentioned here have been translated by the authors into English.

Students had difficulty answering the last two questions in the task that require analysis, evaluation, and creation.

The last two questions were actually a problem for me. Afterwards, why? Well, it's because I didn't understand them. Well, I didn't understand what was expected of the answer, maybe I didn't understand the question. (FG1: S2)

Nonetheless, on several occasions, students mentioned different strategies such as retrieving information using juxtaposition (see FG2: S1). The implementation of these strategies emphasizes students' *metacognitive ability*, which increased during the three activities. The last parameter which may have a contribution on learning and map interpretation, positive (pleasure, motivation) and negative (stress and anxiety) *emotions* were mentioned by the students.

DISCUSSION

THE TAXONOMIC SCORES OF THE DIFFERENT MAP INTERPRETATION components improved, despite the difficulties students had in using the interface at the beginning of the three activities. Studies have pointed out that technical ability may be a hindrance to the use of GSTs (Hong 2017; Walshe 2017). Our findings indicate that technical ability is not a barrier to student learning, even if some adaptation time is required. The progression of overall taxonomic scores from the beginning to the end of the experiment reflects this, as does the statistical modeling of interactions and total scores. The weight of technical ability gradually disappears and highlights a learning effect that becomes stronger over time. This finding is in line with strategies to manage the cognitive load during learning—for example, to use a kind of pretraining to manage the complexity of the learning task at hand (Clark and Mayer 2016). While this has already been reported in previous research (De Miguel González and De Lázaro Torres 2020), our study helps to illustrate this progression (see Figures 5, 7, and 8). Our results contribute to the body of research by providing evidence that web maps support learning geographical thinking by students in secondary schools (De Miguel González et al. 2019; Favier and van der Schee 2014; Metoyer and Bednarz 2017). Confronting our second hypothesis with the analyses, we also found that the web map may mobilize higher cognitive processes. While (digital) maps are generally employed for illustrative

So since I, like, I'm a little bit lame in computers and all that, then as soon as they say you have to do that on the computer or like that, I feel every time I'm completely off the mark and then, the fact to have succeeded in understanding this site, to have found information and all that, that reassured me a little bit, to say to myself in fact finally, that's OK. (FG3: S1)

Despite the difficulties linked to school practices, the mastery of the interactive tool, and the intellectual complexity of the questions, the students still experienced a progression in their learning (see FG1: S1). Nevertheless, given the few focus groups conducted, it is difficult to precisely assess the influence of these additional factors. It is interesting to note, though, that these focus groups allow us to partially confirm and complement a part of the statistical results regarding our hypothesis evaluation while highlighting additional parameters that contextualize the students' learning.

purposes in geography class, taxonomic score progressions highlight students' ability to activate them in analysis and problematization activities.

Our study results highlight several insights and recommendations for the use of web maps in school geography. As we observed with the evolution of scores and interactions, the repetition of similar activities while varying the themes allowed the students to improve their ability to interpret a web map, to analyze, and to problematize. In light of this observation and of the current state of school practices, the use of web maps cannot be carried out as an isolated activity. ***A succession of similar activities leads to a better appropriation of the tool and better learning.*** The progression of taxonomy scores confirms the students' improving ability to use web maps during analysis and problematization tasks. Moreover, during the focus groups, the students repeatedly suggested that this type of activity should be implemented from the beginning of secondary I (the first year of Swiss secondary school, for students 12 years old). According to them, these activities allow them to acquire skills in mastering digital tools that could be useful in their future academic or professional training.

The semiotic and semiological difficulties revealed by the students argue for the ***implementation of a progressive initiation to the types of data representation*** from the least to

the most abstract and according to their criterion of visual aesthetics (i.e., visually attractive), in the following order: choropleth map, proportional symbols, colored proportional symbols.

The data collection and the results of the analysis confirmed that the *map interpretation taxonomy* (see Figures 3 and 4) **could be used to build and evaluate web-based map activities**. Therefore, it could be deployed by (future) secondary I geography teachers. By distinguishing the cognitive processes and levels of knowledge mobilized during cartographic interpretation, the taxonomy helps to set up activities according to the teaching needs and progress of the students. Moreover, this taxonomic differentiation allows (future) teachers to build an evaluation and to follow the evolution of the students' learning. To this end, we advocate the communication of evaluation criteria and comments and the implementation of graphical representations to allow students to monitor their progress.

The recommendations for the development of adapted web mapping interfaces for students are mainly based on the three factors revealed by the PCA (technical ability, ability to investigate and compare, ability to synthesize). Our recommendations are as follows: facilitate mastery of the tool and foster investigation, comparison, and synthesis skills.

Regarding the technical skill, the aim is to facilitate a quick learning curve to reduce the time needed to master the tool, and thus allow students to concentrate on the cartographic interpretation. As a result, the overloading of the interface by providing many interactive features should be avoided. Moreover, the students we observed are used to smartphones and tablets, as opposed to desktop computers. Some of them also encountered difficulties in writing text on a keyboard. During data collection, the availability of tutorials or explanations provided by the researcher or teacher did not result in us observing significant changes in how students used the interface. Therefore, one approach would be to think in terms of user experience and interface without intermediary or external help. As we have seen, the students encountered semiotic and semiological difficulties in interpreting the maps, linked to the type of representation. The majority preferred choropleth maps, feeling that these maps were easier to understand. They also mentioned the use of bar charts on some occasions. This may be related to the representations they usually see in and out of school. Therefore, we propose introducing students to these activities with **a combination of**

minimal representations of choropleth maps and bar charts. Other types of data representations may also eventually be deployed, but students must first be able to rely on adapted representations to support their learning. Instructors could consider making certain other types of representations available, but hidden in the interface and revealed over time, as part of a gradual introduction to more abstract types of data representation—such as from a choropleth map to a colored proportional symbol map, as we suggest in one of our previous teaching recommendations.

Fostering investigation, comparison, and synthesis requires **the implementation of a combination of interactive features from the three types of interactivity** (see Table 1). The results of the statistical analyses and the focus groups underline this. In addition to *spatial navigation* and *loading data*, the integration of the following interactive features is required: *display layer attribute*, *highlight*, and *juxtaposition*. The display of attributes informs students about the extent and spatial distribution of the phenomena represented. Highlighting the data (via a simultaneous map and graph, or with only a map) focuses the student's attention on certain spatial features. To further develop this work, it would be interesting to combine these two cartographic interactions and to study their contribution to learning. *Juxtaposition*, despite its limited use in activities, has an important influence on the ability to compare and problematize. In this respect, one of the most promising interactive features is the provision of two maps side by side on the same screen.

Nevertheless, using web maps does not mean successful or better learning (Jadallah et al. 2017). Task design plays a significant role (Favier and van der Schee 2014). The use of the cartographic interpretation taxonomy (see Figure 2) in collaboration with the partner teacher enabled us to develop intellectually varied tasks. However, there are several limits to be taken into consideration, which add nuance to the significance of the results and the findings. Field access and data collection conditions were challenged by the constraints of the COVID pandemic. The work discussed here is an exploratory case study and thus the context of the experiment plays a significant role. The experimental conditions were kept as close to the field as possible to obtain similar data to the reality of teaching. We did not use a protocol that separated the tasks in time according to the levels of knowledge and cognitive processes identified in our map interpretation taxonomy. While the division of the tasks follows an intellectual progression, the students

did not necessarily answer the questions in the suggested order. Another limitation is the relatively small sample size ($n = 20$) which prevents the results from being generalized, but nonetheless provides leads from which other, larger studies could be conducted. Moreover, the inference from mouse movements to cognition is debated in the literature. Design factors of the mouse tracking procedure may hinder the manifestation of cognition through movement (Grage et al. 2019; Schoemann et al. 2019). The partner teacher in this research is perhaps not typical of his colleagues: his keen interest in setting up innovative ways of learning differ from usual practices. Finally, the layout was modified during the three activities according to feedback from students and the teacher to meet their needs. Despite the minor extent of the modifications made, this element may have led to bias in the data collection.

Nonetheless, we still consider our theoretical and methodological approach to be relevant, as it opens interesting research perspectives. Here are a few suggestions for achieving this:

- a precise order of execution and division of tasks as well as a fixed time (determined following an exploratory survey),
- a group of participants numbering at least 100,
- the use of one or more control groups to guarantee the significance of the results,
- ensuring that the mouse tracking device limits interference between mouse movement and cognition (Grage et al. 2019; Schoemann et al. 2019), and
- reducing the interactive visualization options in order to better evaluate and analyze the contribution of interactivity to learning.

It would also be possible and interesting to limit experiments to specific interactive functionalities to better understand their influence on learning, as highlighted by our study on juxtaposition. Finally, a study with a similar methodology, comparing static and interactive maps, could use eye tracking to gather data on their respective contributions to learning.

CONCLUSION

THIS EXPLORATORY STUDY IS A FURTHER STEP IN THE research undertaken so far to better understand the role of interactivity on the construction of knowledge in geovisualization, and on learning geographical thinking in geography education. Our research differs from previous studies by focusing on the effect of interactivity on learning with qualitative and statistical analysis. To the best of our knowledge, this essential feature of web maps has not yet been investigated among secondary I students. The results highlight interactive behaviors and interactions that contribute to student learning. The statistical results—PCA and bivariate—provide interesting information about how the mobilization of interactions supported student learning. They highlight that the contribution of cartographic interactions is related to a combination of all three types of interactivity (see Table 2). Temporal PCAs were performed to identify interactive behaviors that were most likely to enhance student learning. These analyses provided information on the frequency of mobilization of the interactive features. The temporal PCAs of four of these interactions—*spatial navigation*, *display layer attribute*, *spatial navigation move*, and *highlight*—reveal that when one of these four interactions is mobilized in a moderate and intermittent way throughout the activity, it has a moderate

to a significant positive impact on the scores. The *juxtaposition* analysis differs, suggesting that only a slight mobilization may lead to a moderate impact on problematization and connecting. These observations are summarized in Figure 9, which shows the interactive behaviors with the most contribution to learning. Focus groups complement and partially confirm the results revealed by the statistical analyses. While supporting the influence of technical ability and interactivity on learning geographical thinking, they highlight the involvement of other factors. This additional information points towards the importance of activity context through school practices and the intellectual complexity of the tasks. The focus groups revealed several details of students' interactions with the web maps: their difficulties in interpreting specific graphs, ability to identify obstacles and work around them (metacognitive ability), visual aesthetic preferences, and the role of both positive (pleasure, motivation) and negative (stress, anxiety) emotions. According to the state of the art by Montello et al. (2018) in this respect, emotions play a central role in the map interpretation. Further investigations would be necessary to evaluate more precisely the respective weight of these factors revealed by the focus group analysis. At this stage, these are only indications. The combination of

analysis and data collection methods allowed us to better understand the role of interactivity by confirming and complementing our statistical results, while highlighting the existence of other learning factors through the focus groups. These focus groups highlighted other factors missing from the hypotheses related to the context of the

experiment and student characteristics. We are convinced that this type of methodological and theoretical articulation is appropriate and relevant to study the contribution of web mapping, and possibly digital tools on students' learning.

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